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Modularity of the MIT Pebble Bed Reactor

For Use by the Commercial Power Industry

By

Jaime E. Hanlon- Hyssong

B.S. Marine Engineering
US Naval Academy 2000

SUBMITTED TO THE DEPARTMENT OF NUCLEAR SCIENCE AND ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN NUCLEAR SCIENCE AND ENGINEERING

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 2008

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
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4. TITLE AND SUBTITLE

Modularity of the MIT Pebble Bed Reactor For Use by the Commercial Power Industry

5a. CONTRACT NUMBER

N62271-97-G-0026

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Jaime E. Hanlon- Hyssong

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Massachusetts Institute of Technology

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Postgraduate School
Monterey, CA 93943

10. SPONSOR/MONITOR'S ACRONYM(S)

NPS

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

1. DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Modular Pebble Bed Reactor is a small high temperature helium cooled reactor that is being considered for both electric power and hydrogen production. Pebble bed reactors are being developed in South Africa, China and the US. To make smaller 120 Mwe reactors economically competitive with larger 1500 Mwe traditional light water reactors changes in the way these plants are built are needed. Economies of production need to be sufficiently large to compete with economies of scale. MIT (Berte) has been working on developing a modular design and construction strategy for several years. This thesis builds on that work by demonstrating the technical feasibility of implementing the modularity approaches previously developed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	113	Sean Tibbitts, Educational Technician
					19b. TELEPHONE NUMBER *(Include area code)* (831) 656-2319 civins@nps.edu

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Modularity of the MIT Pebble Bed Reactor

For Use by the Commercial Power Industry

By

Jaime E. Hanlon-Hyssong

Submitted to the Department of Nuclear Science and Engineering on May 19, 2008 in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Science and Engineering.

Abstract

The Modular Pebble Bed Reactor is a small high temperature helium cooled reactor that is being considered for both electric power and hydrogen production. Pebble bed reactors are being developed in South Africa, China and the US. To make smaller 120 Mwe reactors economically competitive with larger 1500 Mwe traditional light water reactors changes in the way these plants are built are needed. Economies of production need to be sufficiently large to compete with economies of scale. MIT (Berte) has been working on developing a modular design and construction strategy for several years. This thesis builds on that work by demonstrating the technical feasibility of implementing the modularity approaches previously developed.

The MIT approach uses "space frames" containing all the components, piping, valves and needed cables, instrumentation in a specified volume. These space frames are built in a factory to assure high quality in manufacture. They are then shipped by train or truck to the site and assembled "lego" style. It is expected that with the improved quality in the factory setting, and rapid assembly at the site that the total time and cost of construction of the plant will be greatly reduced (Kadak). To make this process work, it is vitally important to assure that when the space frames and internal components are manufactured, they are done to rigid tolerances to assure line up when assembled in the field. By using many advanced three dimensional measurement technologies, including the use of digital photography, lasers, and photogrammetry, companies are now capable of fabricating pieces to extremely precise specifications at a relatively affordable cost.

This thesis evaluates the feasibility of manufacture of space frames and internal components to the required tolerances, the accuracy control needed and how the plant can be assembled with details of each space frame interfaces. A global reference system was determined and a basic plant map for space frame placement developed. Deviations from exact placement from this map due to tolerance allowances were factored in and methods and techniques for overcoming any variations was developed. In order to enable each frame and it's respective components to be accurately fabricated to ensure interfacing parts will mate, a local coordinate system was developed for each frame and used to describe the exact location of the required interfaces for each specific frame. Crucial concepts of accuracy control and "best fit" are outlined and incorporated.

Based on independent verification of the processes and the design proposed, this modularity approach appears to be feasible. A comparative economic analysis was also performed to assess the potential cost savings of the modularity approach compared to traditional "stick build" approaches presently being used in nuclear construction. Manhour, learning curve and overall cost savings of over 30 % can be expected which suggests that if modularity approaches as those proposed are used, smaller reactors can compete with larger economies of scale plants.

Thesis Supervisor: Andrew Kadak
Title: Professor of the Practice, Nuclear Science and Engineering

Thesis Reader: Ronald Ballinger
Title: Professor, Nuclear Science and Engineering

Acknowledgements

As with any thesis prepared which is based on previous work, collaboration between previous authors and professors proves to be an invaluable and essential tool. The author would like to recognize the technical assistance and support provided from individuals involved with this thesis' development.

Thanks to my advisor, Prof. Andrew Kadak, whose patience and support are largely responsible for the contributions contained within this thesis. His continuous stream of ideas and references were highly instrumental.

Thank you to Pete Stahle, whose understanding of Solid Edge, and numerous hours of previous and current of effort resulted in many of the three dimensional drawings included within this thesis.

My most sincere gratitude to the entire project team at General Dynamics Electric Boat who provided some guidance and important feedback. Their practical knowledge in modular construction of nuclear submarines was invaluable and not only proposed but added credibility of many ideas included in this work.

I, like many students at MIT, are indebted to the many wonderful teachers I have had throughout my life, who instilled a joy in learning at an early age and continued to challenge and interest me throughout my education. Of particular note are my undergraduate Marine Engineering professors who sparked a deep interest and fostered my excitement in nuclear power and power systems. Their candid, yet practical approaches to energy conversion continue to inspire me.

Finally, thank you to my family and close friends whose support of my studies at MIT continued to be unwavering during my thesis preparation and whose sense of humor and constant encouragement were crucial to the success of this work.

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List of Abbreviations

AC	
BWR	Boiling Water Reactor
cm	Centimeters
C	Celsius (Centigrade)
CNC	Computer Numerically Controlled
cm	Centimeters
EDM	Electronic Distance Measuring Device
EROM	Engineering Rough Order of Magnitude
Ft	Foot or Feet
GDEB	General Dynamics Electric Boat
HAZ	Heat Affected Zone
He	Helium
ID	Inner Diameter
IHX	Intermediate Heat Exchanger
in	Inch(es)
K	Kelvin
NDT	Non-Destructive Testing
NRC	Nuclear Regulatory Commission
OD	Outer Diameter
OTAR	Out of Tolerance Report
PCMM	Portable Coordinate Measuring Machine
m	Meter(s)
MIT	Massachusetts Institute of Technology
MPBR	Modularized Pebble Bed Reactor
NRC	Nuclear Regulatory Commission
OD	Outer Diameter
Pa	Pascal
PSI	Pounds of Pressure per Square Inch
PWR	Pressurized Water Reactor
PBR	Pebble Bed Reactor
PSI	Pounds per square inch
PWR	Pressurized Water Reactor
RV	Reactor Vessel

1 Introduction

1.1 Motivation

For many reasons, The United States, along with many other nations, is increasingly seeking methods for electricity production that does not involve fossil fuels such as coal, oil, or natural gas. Environmentally, the desire is to decrease the carbon emissions associated with coal and natural gas plants.. Economically, this is driven by the escalating high price of fossil fuels and the impact of these increases on the average family, business, and consumer products. Additionally, political and national security issues surrounding the affordable acquisition of such fuels has taken the spotlight. Thus, the desire for increased use of alternative energy sources has grown.

At present, there is great anticipation for a "nuclear renaissance" in the United States. Eight new license applications for 15 new light water reactors have been filed with the Nuclear Regulatory Commission. Utilities and merchant generating companies have identified sites for these new plants and are now in the process of developing plans to actually build these reactors. The smallest of these new reactors is the Westinghouse AP 1000 at 1100 Mwe with the largest being the General Electric ESBWR at 1,700 Mwe. Estimates for the construction time ranges from 4 to 6 years with costs ranging from $ 3 to over $ 6 billion per plant.

The MIT Modular Pebble Bed Reactor (MPBR) has taken a different approach to new reactor design, construction and operation. [Kadak]. The approach is to use high temperature helium gas as a coolant allowing for 50% higher thermal efficiency and smaller modular reactor that can be built quickly with a significantly smaller capital investment. At 120 Mwe, each plant can be built within a three year period with a capital outlay of about $ 300 million allowing for easier acceptance by the financial community, more manageable risk and an opportunity to expand the power modules as needed to meet demand at the same site. The pebble bed technology was chosen due to its "meltdown proof" design allowing for a less costly plant, online refueling which

deccreases power generation interruptions and greater public acceptance. [Kadak 1998]

The overall goal of modularizing the pebble bed reactor is to decrease the construction cost of a new plant, and minimize the impact of repairs by being able to change out a single module without impacting the structure of the plant.

For the commercial power industry, the motivation to build new nuclear reactors is significantly diminished by the high capital cost and time to bring plants on line. One way to defray these costs is to utilize the economics of mass production. In order to facilitate this, the nuclear reactor design must be modularized - broken into separate components that are designed to fit into a standardized frame which can then be put together in a more simplistic "plug and play" fashion. [Berte] By building multiple, smaller plants, the utility can begin to generate power quickly and thus generate revenue while other modular plants are being constructed to meet increasing demand. This concept addresses several important factors which create obstacles to new nuclear plant construction: [1] high initial capital costs – instead of multiples of billion of dollars, multiples of hundreds of millions; [2] time to build – this affects the money at risk and the need for additional financing to cover increased cost of money for the longer duration; [3] Overcapacity – it is rare that a utility needs 1500 Mwe on their grid at once. With the smaller modular plants on the same site capacity can be added in realistic increments as needed keeping overall generating costs lower, [4] Credit and financial ratings of utilities – few utilities have capitalization that can afford to finance $ 6 to $ 12 billion plants; [5] Ongoing maintenance costs – repairs at nuclear installations are very expensive and outages can be lengthy. The modular concept being developed utilizes a replace modules rather than repair strategy. This should improve the attractiveness of nuclear technology to utilities.

1.2 Objective

The objective of this thesis is to develop a more detailed space frame design and interfaces that can be built economically for the power conversion system building on the previous work of Berte and Kadak in 2004. This will entail assessing the technological capability to manufacture the space frames and the placement of internal components

such that they can be matched to adjoining space frames using the assembly strategy outlined. In addition, while detailed economic analysis can not be done at this stage, a comparative economic analysis using the same principles of modularity in manufacture of today's advanced nuclear submarines will be performed to identify potential savings of this approach. This thesis will take advantage of today's integrated design, engineering and manufacturing capabilities using an essentially paperless design process to assure improved quality and reduction in costs.

This thesis will first summarize previous work conducted on this project as well as the benefits of the PBR plant, modularity and how to apply it to the PBR. A review of how the submarine construction industry has taken advantage of modularity will made to identify whether the concepts proposed herein can be implemented. The implementation of the space frame integration method will be evaluated using a local frame and global plant reference systems. Support systems, joining techniques, concepts required for modular construction will be defined including "constant flow of best fit" approach to assure lineup of space frames and the internal components. Also described will be the process of accuracy control- the detailed process for ensuring that modules will interface with mating parts. Finally a comparative cost analysis will be made comparing modular construction versus traditional methods. The overall objective is to show the feasibility and practicality of modular construction in the nuclear power industry.

1.3 Summary of Previous Work

1.3.1 Background of previous work

In 2004 Marc Berte completed a Masters of Science in Nuclear Engineering at MIT while working with Professor Andrew Kadak. The thesis was titled "Modularity in Design of the MIT Pebble Bed Reactor" [Berte].

His extensive thesis was a significant step toward transforming the construction of Pebble Bed Reactor (PBR)PBR power plant to a modularized method. Modularity of this plant, its construction and economic benefits, are discussed in much detail throughout

this thesis, but this section focuses on the findings of Berte's thesis with a focus on areas that were further developed in this work.

1.3.2 Previous Findings

Berte was able to conceptually arrange the power conversion system of MIT's version of the pebble bed reactor into a space frame configuration whose design constraint was that each "set" of components (space frame and its contents) could be reasonably shipped by train or truck in the United States. This involved determining the weights and sizes of the individual components that could be incorporated into and individual module and shipped. The original design of the MIT pebble bed reactor is a high temperature helium cooled reactor using a Brayton Gas cycle plant with intermediate helium to helium heat exchangers providing 900 C helium to gas turbines and compressors in a recuperated and intercooled cycle. Figure 1 is a plant schematic of the design with key parameters shown.

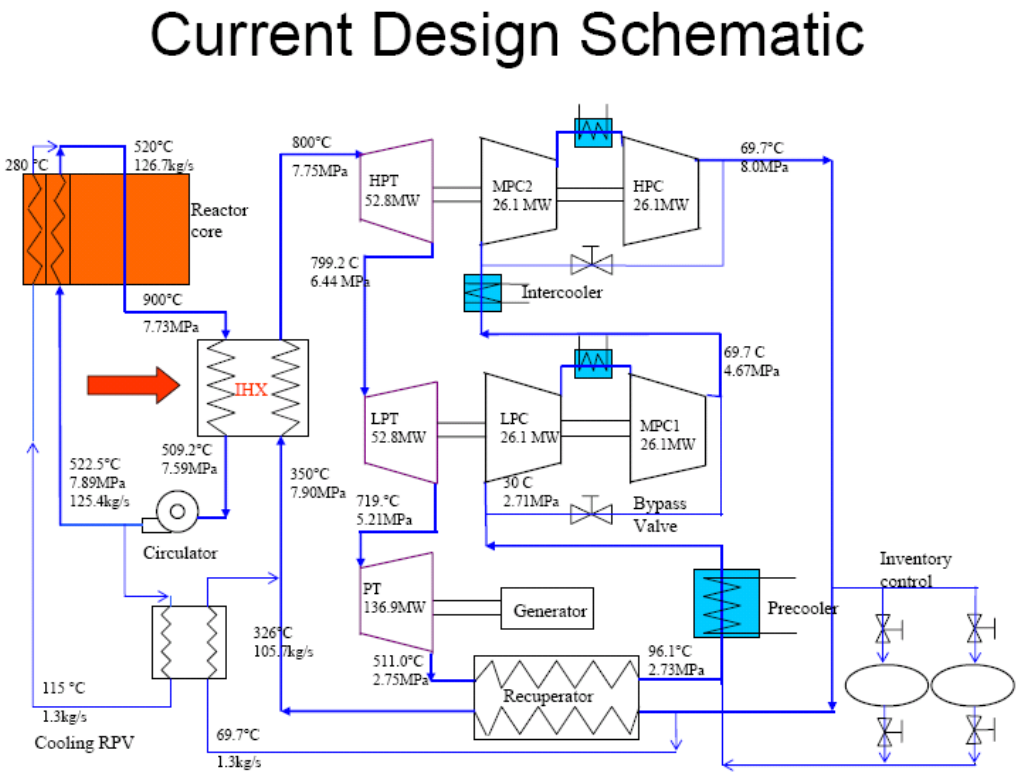

Figure 1: Current Plant Schematic [Kadak]

When translated into modular units that fit the modularity constraints, the plant is graphically shown in Figure 2 which is an earlier version of Berte's design. This figure shows, outlined by the dotted lines, what components are in the shippable size. As can be seen, instead of one or two intermediate heat exchangers, six are needed to fit the weight and size limitations.

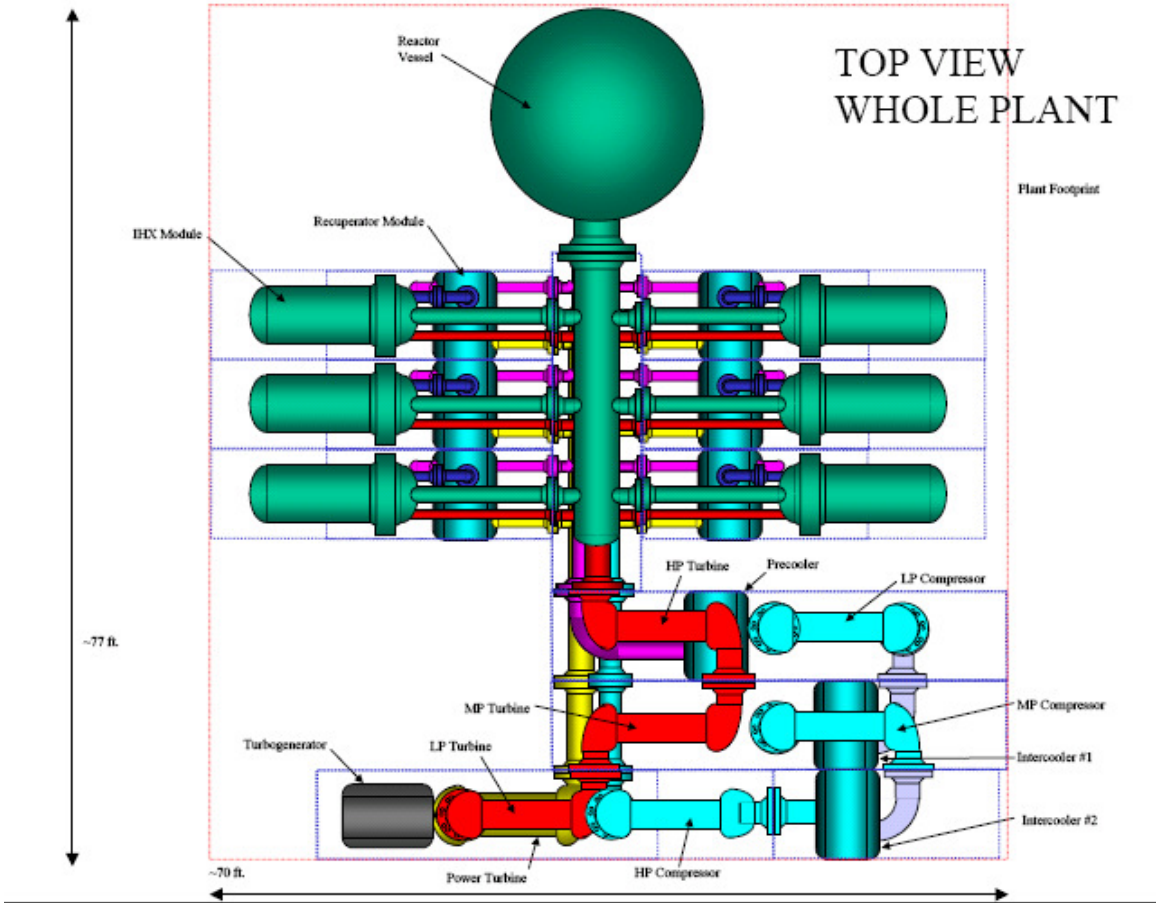

Figure 2: Top Down View of Plant Layout [Kadak]

Using this as a framework for design, the final version of the plant after thermal stress analysis is shown on Figure 3. This figure identifies the key components and approximate location in the overall plant configuration which will be analyzed for feasibility in this thesis. Shown in green are the connection points between the components that would ultimately be contained in space frames.

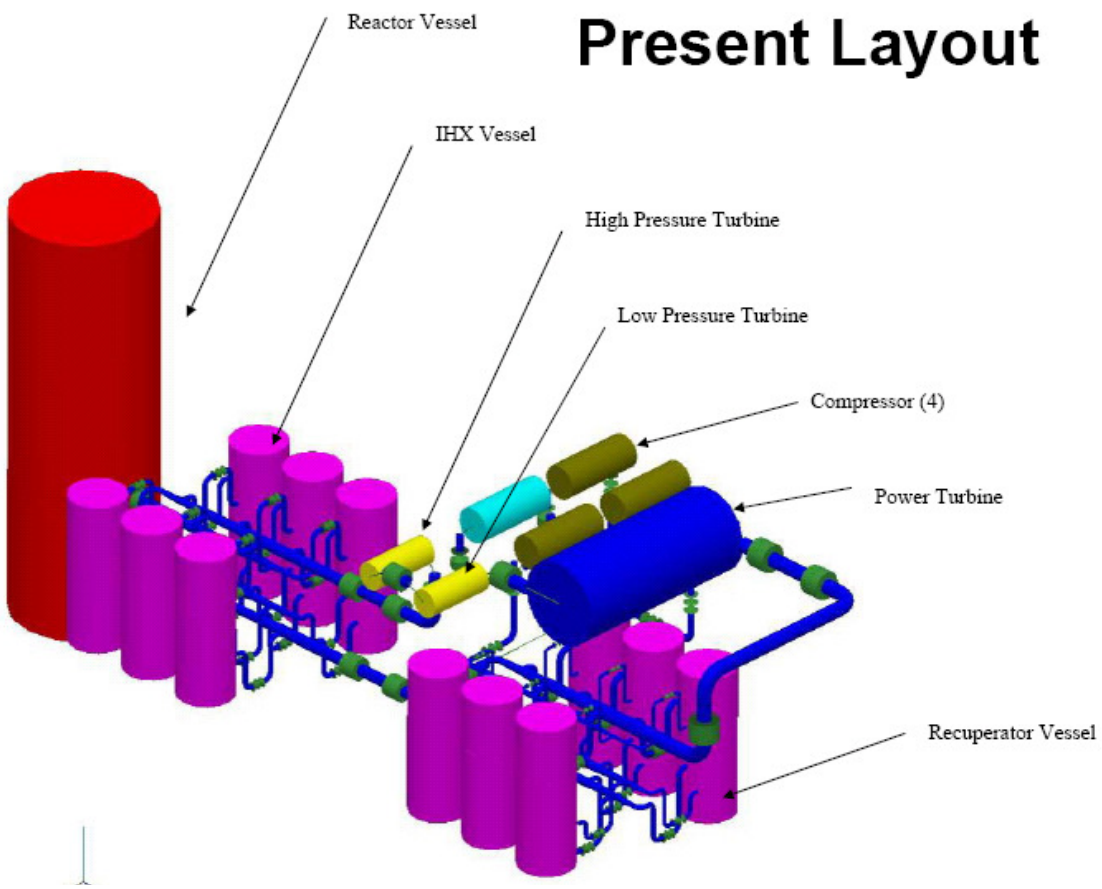

Figure 3: Three Dimensional MPBR Configuration [Berte]

The space frame is typically a rigid empty structure shown in Figure 4 in concept. These would be manufactured to a standard size and used to provide support to the systems and components contained inside.

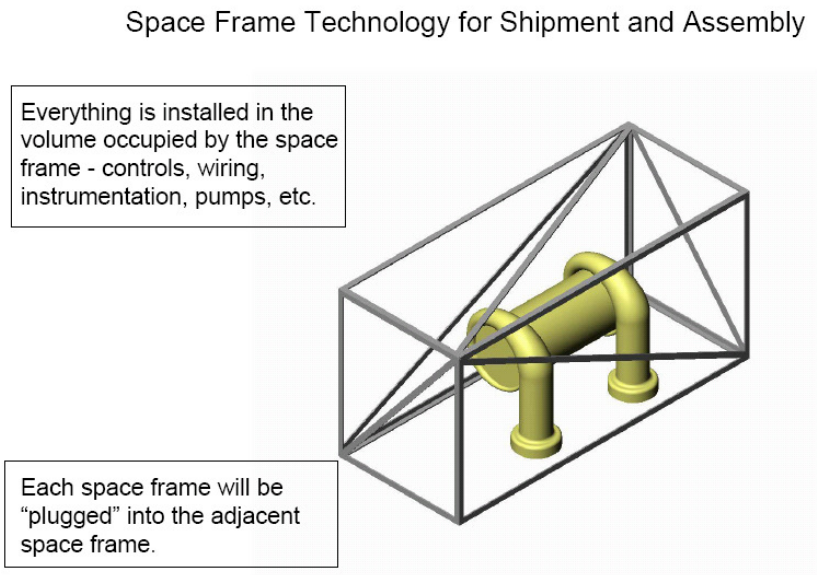
Space Frame Technology for Shipment and Assembly
Everything is installed in the volume occupied by the space frame - controls, wiring, instrumentation, pumps, etc.
Each space frame will be "plugged" into the adjacent space frame.

Figure 4:Typical Space Frame Configuration [Berte]

When this plant is placed into space frames, Figure 5 shows the proposed configuration.

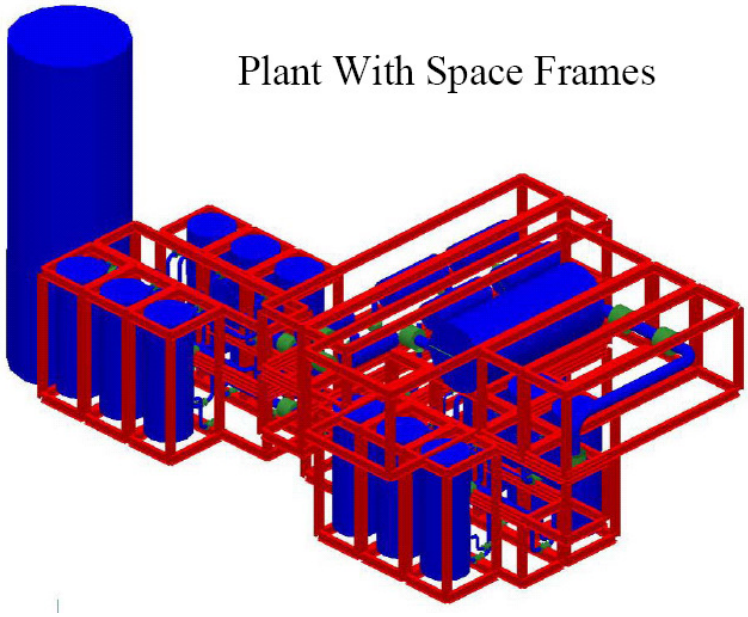

Figure 5: Plant with Space Frames [Berte]

Figures 6 and 7 show isometric layouts of the overall plant configuration in various selected views.

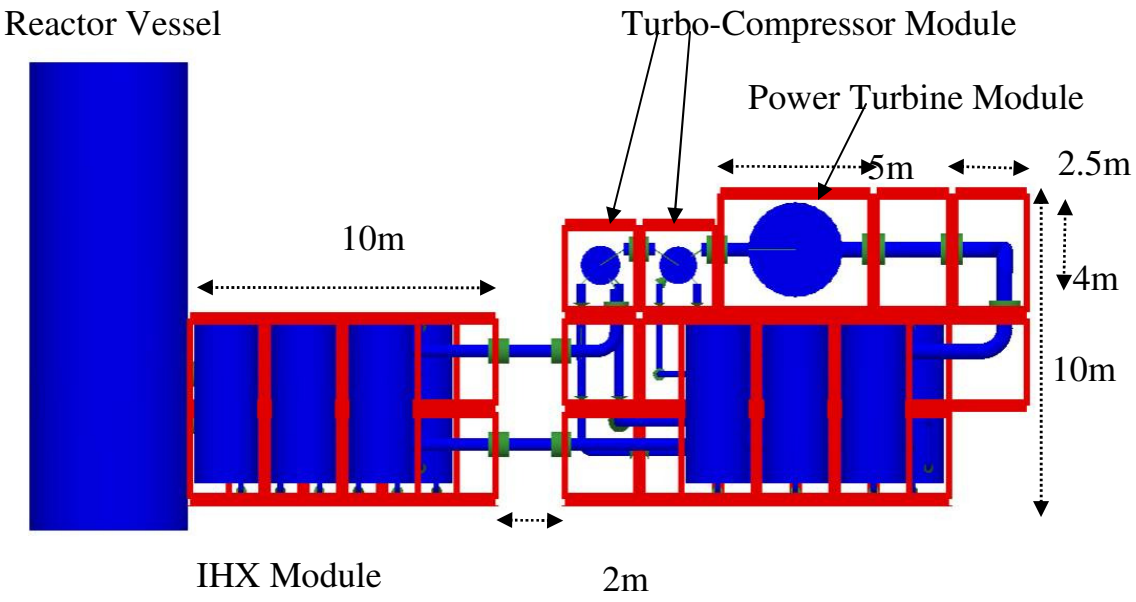

Figure 6: Isometric Layout of Plant with Space Frames [Berte]

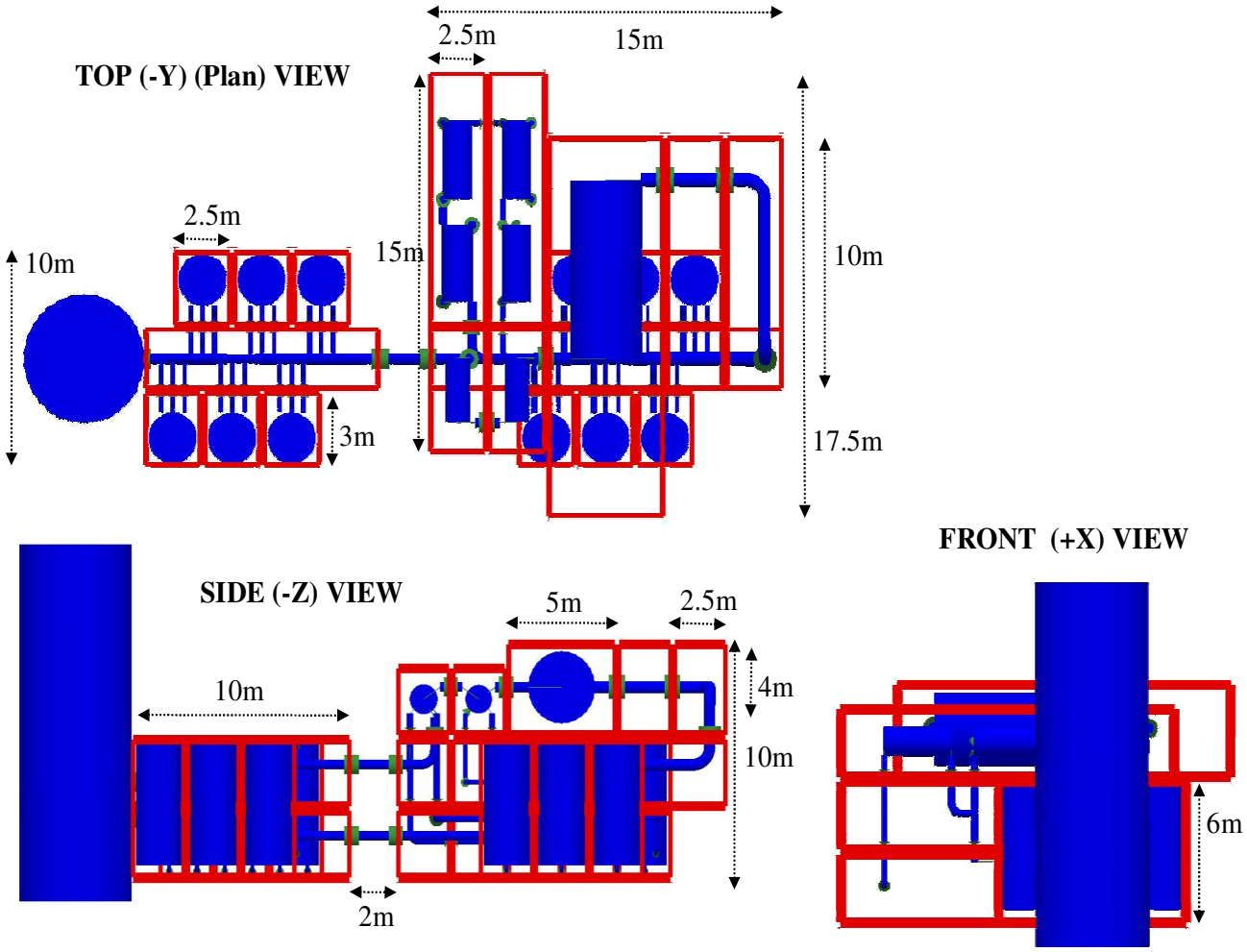

Figure 7: Top, Side, and Front Views of the Plant with Space Frames [Berte]

The Intermediate Heat Exchange side of the plant is shown below in Figure 8 without space frames. This extensive assembly accurately describes all of the intricate inter-workings of the components and how they come together and developed using the engineering software *Solid Edge* by Peter Stahle, a Research Engineer in MIT's Nuclear Science and Engineering Department.

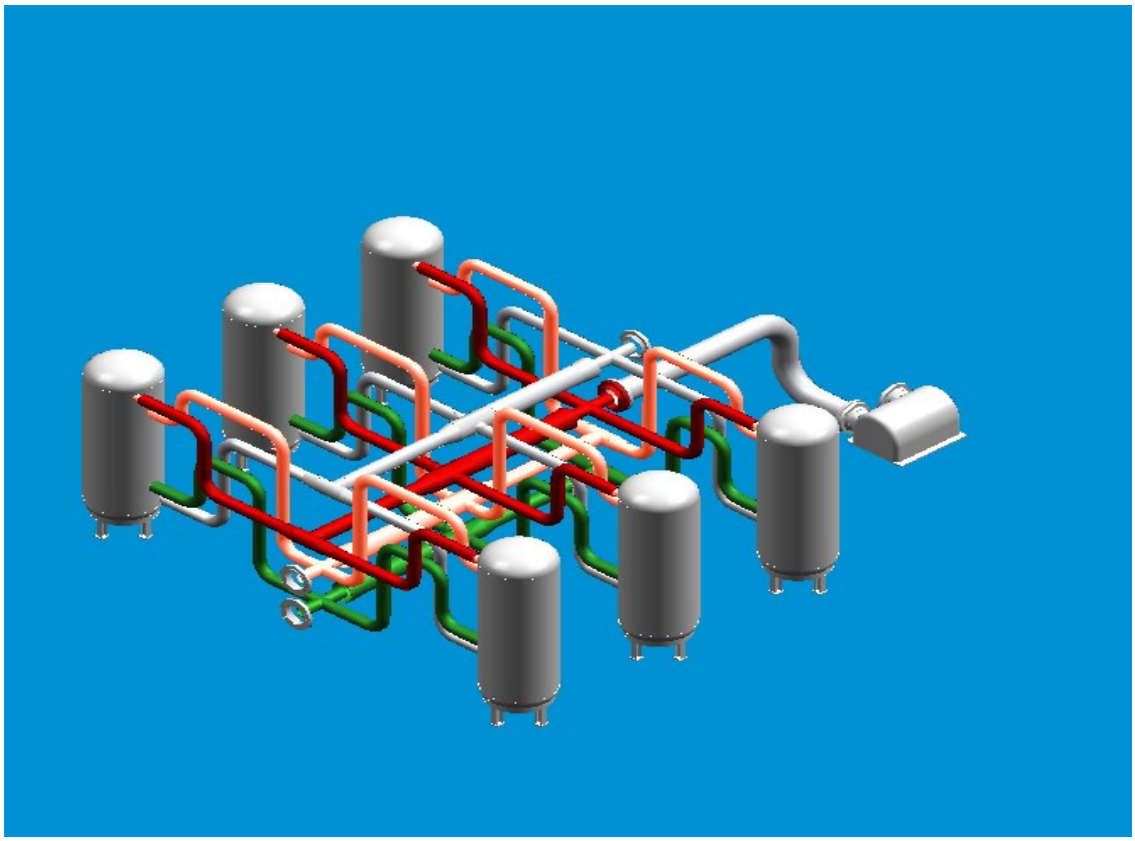

Figure 8: : Detailed IHX- Side Assembly, Showing Following Piping- Primary Inlet (Pink), Primary Outlet (Green), Secondary Inlet (Grey) and Secondary Outlet (Red) [Stahle]

1.3.3 Space Frame Concept for Modularity

The integrated use of space frames is best summarized in Figure 9 from Berte. As can be seen it utilizes a standard shipping container size that could be mass produced for use by the component vendor or some central plant integrator. Weight limits are clearly defined for truck or train shippable components. Stacking limits are defined as is the requirement that these space frames are self supporting structural members that would be installed in rooms without the need for more rigorous seismic supports to existing structures which would greatly simplify construction. Berte originally called for the use of flanges for connections of piping. This was seen as a desirable feature provided that is was feasible and not overly costly. This thesis evaluates this.

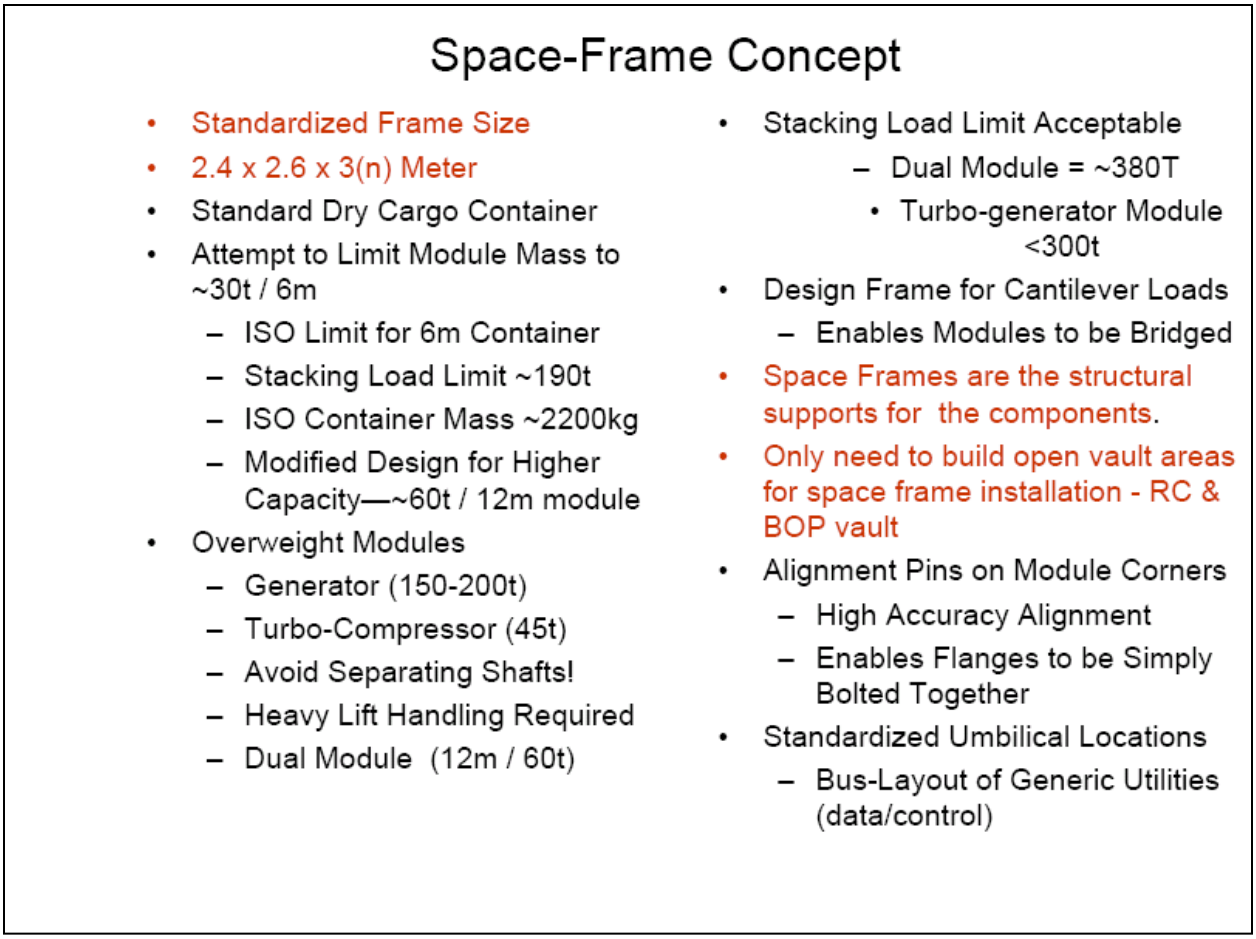
Space-Frame Concept
Standardized Frame Size
2.4 x 2.6 x 3(n) Meter
Standard Dry Cargo Container
Attempt to Limit Module Mass to ~30t / 6m
ISO Limit for 6m Container
Stacking Load Limit ~190t
ISO Container Mass ~2200kg
Modified Design for Higher Capacity—~60t / 12m module
Overweight Modules
Generator (150-200t)
Turbo-Compressor (45t)
Avoid Separating Shafts!
Heavy Lift Handling Required
Dual Module (12m / 60t)
Stacking Load Limit Acceptable
Dual Module = ~380T
Turbo-generator Module <300t
Design Frame for Cantilever Loads
Enables Modules to be Bridged
Space Frames are the structural supports for the components.
Only need to build open vault areas for space frame installation - RC & BOP vault
Alignment Pins on Module Corners
High Accuracy Alignment
Enables Flanges to be Simply Bolted Together
Standardized Umbilical Locations
Bus-Layout of Generic Utilities (data/control)

Figure 9: Highlights of Space Frame Modularity Concept

Inside each of these space frames, which could be oriented in any direction, will be set(s) of components and their required piping, etc. Figure 10 shows a basic space frame, oriented in different positions.

Space Frame Design

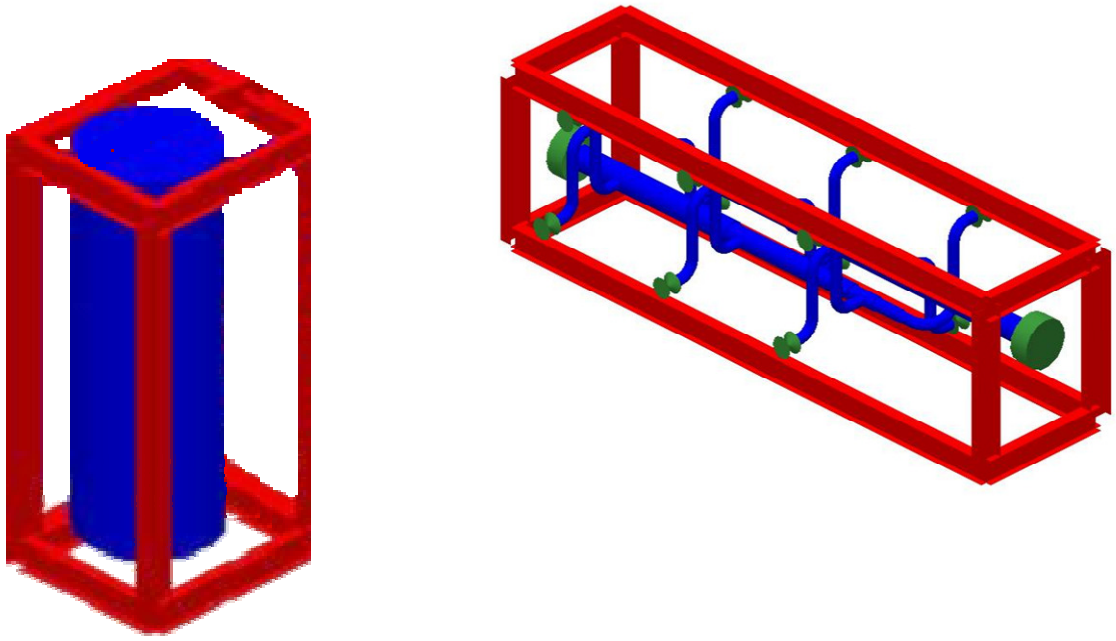

Figure 10: Basic Space Frame in Two Different Orientations, Based on the Equipment Housed Inside. [Berte]

Some space frames will require support plates to hold the components in place as shown on Figure 11. The goal of this thesis is to develop a design for each space frame for the power conversion system, identify the connecting make up piping requirements that are feasible to assure proper lineup and connections. Most of these components need to remain flexible in their structure since this design should be able to adapt new components as they are developed. One of the main goals of this modularized plant is to

have the ability to switch vendors during production, if needed, or upgrade after installation. This thesis therefore focuses on showing the capability of one design while ensuring flexibility.

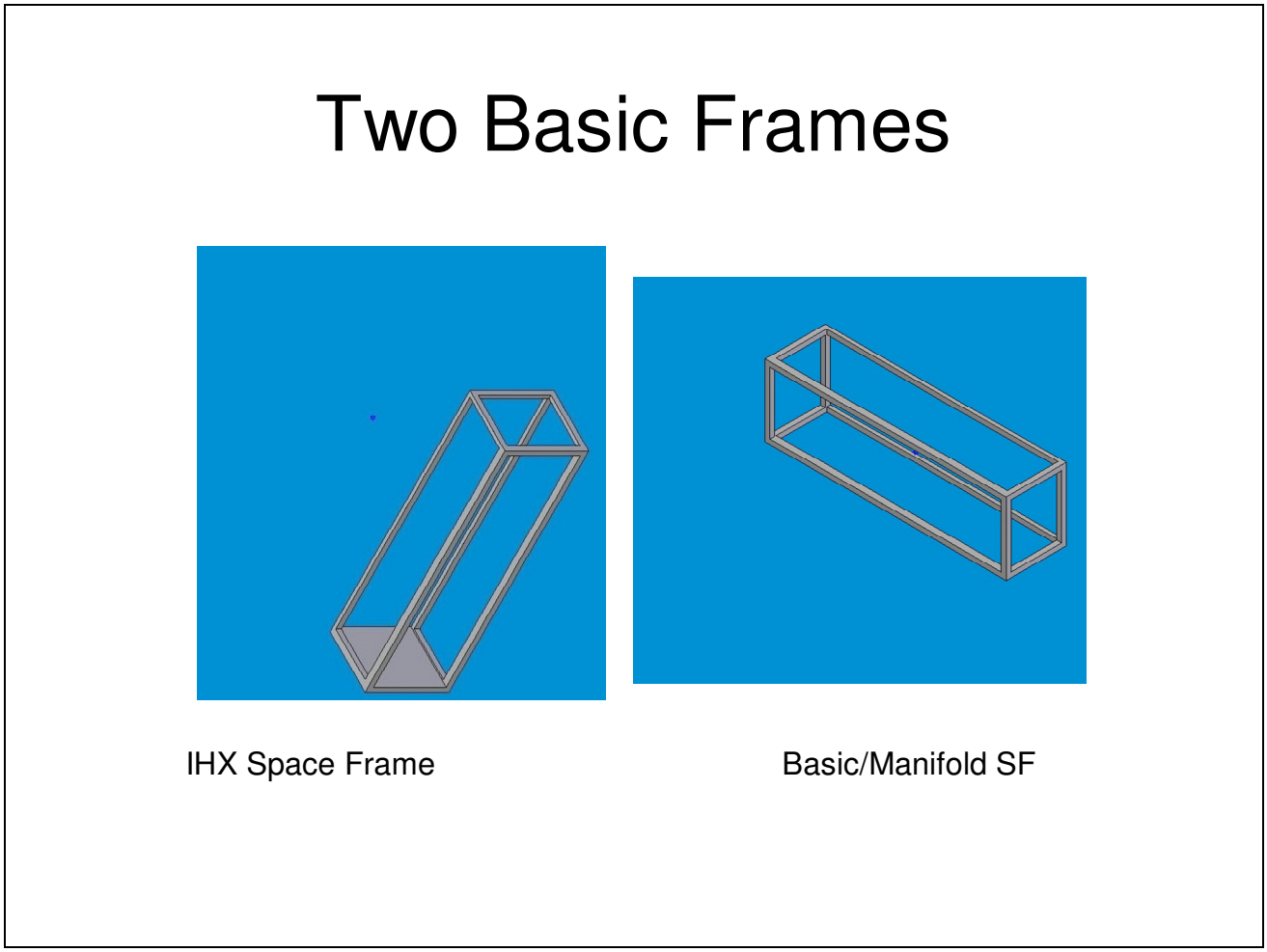

Figure 11: Two Basic Space Frames- The IHX Frame has a bottom plate, while the basic frame (right) is completely empty.

1.4 Organization of this thesis

This thesis first discusses general considerations for engineering design, fabrication, and construction of complex systems. These considerations and guidelines are then applied to our effort to modularize the Pebble Bed Reactor. Details of the IHX and power conversion sides of the plant, including the components housed in each space frame are described. Most importantly, the location of interfacing components for fabrication purpose and plant integration are listed. Finally, a cost analysis discusses the potential savings seen by building a Pebble Bed Reactor plant in a modular-versus traditional- fashion.

2 Modularity

2.1 Modularity- Overview

From oil rigs to nuclear powered submarines, modularity has shaped the way construction of many large scale projects is developed and carried out. The appeal of modularity in construction is that it allows the construction process to occur quicker and with less expense compared to traditional "stick built" construction techniques. To make a system modular requires breaking down that system into independent and separable components that can be assembled individually in mass quantities and then placed into the system. This concept is somewhat akin to the production assembly line, but instead of having a product at the end of the line, the product is completed away from the manufacturing assembly line. Modularity is used extensively on smaller scales for electronic equipment. These "Commercial Off The Shelf (COTS)" units can be replaced, swapped and upgraded with minimum effort.

One of the main advantages of modularity is the ability for the product to be adapted or upgraded. This is applied in the navy's design of ships and weapons systems. As stated by James E Turner (Navy) it "means that, no matter how threats or technologies evolve, we will always possess a range of options with which to address new challenges" [Carey]. The result is a cost savings and flexibility. Also, modular construction allows for a reduced number of skilled, specialized, and premium paid laborers at the construction site, while building simultaneously in various locations, leading to reduced overall cost due to shortened construction schedule and less premium pay. General Dynamics Electric Boat has proved a "1-3-8" rule [GDEB 1]. According to this rule, a given job takes only one hour to complete in the shop, three hours in a module and eight hours to complete on site.

For a system to be constructed using modularity there are some crucial requirements. First, the system must be designed to be built in a modular fashion. In order to do this, a system must be broken into sub-modules, such that each sub-module can be built and tested separately as a stand-alone unit. [GDEB 1] Also, the components

or systems that makeup a specific sub-module must meet their own tolerance requirements while ensuring that when combined with other sub-modules, they perform as an integrated system. These tolerances should start at the core of the design and account for the "ripple effect" of multiple layers of modularity on the compounded tolerances. Balancing the cost trade-off for tighter tolerances vs. looser tolerances will be a necessary step during the design phase as each component or system within a sub-module will have different tolerance requirements. [GDEB 3]

For the Pebble Bed Reactor power generating system which is the focus of this research, the above criteria translates into ensuring the tolerances are built-in to ensure piping mates with piping and space frame meets space frame, as appropriate. To assure cost effective fit up, lengths of pipe with at least one change in direction, i.e. a bend, are designed into the system to provide the desired flexibility. [GDEB 2]

The second requirement is that there are fixtures that are designed to be reused to ensure the proper location and alignment with mating components or sub-modules. These reusable fixtures, or "jigs", will be used in the manufacturing process to ensure the ultimate placement of the part within the system is accurate. Should the initial fabrication of the component be "off", these reusable fixtures will demonstrate that and the component can either be refabricated or adjusted to fit within acceptable tolerances at the factory and not in the field. [GDEB 2, 3]

The final requirement for the success use of modularity is accuracy control. [GDEB 4] The tolerances need to be budgeted so when all possible deviations from specification are within the maximum allowable tolerance, the system can be constructed properly. That is, take the maximum allowable deviation for the assembly to work, and then calculate the maximum allowable deviation for each level of assembly back to the smallest component. Further, a schedule for measuring how these tolerances are met during the manufacturing process needs to be determined and allow ample time for out of tolerance conditions to be discovered and corrected at every step of the assembly process. [GDEB 4] In order for this to occur, global and local reference systems need to be incorporated into the design and an on-site grid should be set up at the construction site.

For this design, the global and local reference systems are described in detail in Section 4.2.

2.2.2 Applying modularity to the Pebble Bed Reactor

The basic unit of the Pebble Bed Reactor power plant will be "space frames". These frames are typically 10m x 3m x 2.5m so they can be transported via train or flat bed truck (perhaps heavy haul as needed from rail siding) to the site. Each will house a single major component and support equipment. The space frames, along with the pipes, need to be built according to a plan within the associated tolerances. These frames will need to have reference lines on them which will simulate the frames actual location on the construction site, in order to help align the units. The components and piping will be placed in the space frames to budgeted tolerances and will be measured prior to final shipping for both the frames and its contents.

On site, the foundation or keystone for each portion of the system (the heat exchange and power conversion sides) will be placed at the most precise and accurate location as determined by the drawing requirements and an established a global grid reference system. In the case of the PBR, the IHX and recuperator manifolds will act as these keystones. Next, the remaining space frames will be placed relative to this established grid. Finally, the modules will be joined together directly or by using make-up piping and inter-frame supports, which are discussed in detail in sections 3.2, 3.3, and 3.4. [GDEB 3]

2.2.3 General Dynamics Electric Boat as a Modularity Leader

In the 1990s the U. S. Navy began developing the SEAWOLF submarine, the next generation submarine. After the Cold War, the security role and needs of the Navy changed. Additionally, the budget for new construction of submarines decreased dramatically. As a result, the next generation of submarines needed to be designed with changing missions in mind and needed to be constructed at a lower cost than before. [Carey]

Having constructed the nation's first submarine in 1900 and constructed 15 classes of nuclear submarines, and all but one of the 19 classes of nuclear power plants, General Dynamics Electric Boat (GDEB) has a long history of nuclear submarine construction. Due to increased cost pressure GDEB had a great incentive to develop a method to overcome the challenge of constructing submarines that require flexibility in order to adapt to an ever-changing threat, but also to do so at a dramatically reduced cost. Needless to say, this required a revolutionary approach to submarine design and construction which had historically been piece by piece "stick build" construction which was very labor intensive, time consuming and costly. [Carey]

Instead of changing the submarine, GDEB changed its approach to submarine construction. Capturing the already acquired experience of electronics, aerospace, and the oil industry, GDEB comprised a process that utilized concurrent engineering, integrated product teams, and modular design and construction, a concept they had pioneered over twenty years earlier during the construction of the Trident class, and continued to develop during other classes of construction. [Carey]

In addition to using integrated product teams and advancing computer tools would to achieve this goal, the key to success would prove to be the switch to a modular design and construction philosophy. By integrating design, engineering and manufacturing into a seamless software product for planning, scheduling, procurement and manufacturing, they were able to improve overall performance. For this philosophy to become a reality GDEB, in addition to utilizing these cutting edge technologies, some of which would enable the visualization of features and design, they enabled the design process to be streamlined and ensure both customer and builder "see" the same results long before the actual product is built. CAD systems, like "Spacial Analyzer" make this visualization possible. This ensures that re-work is minimal and enables them to then take a basic design and vary it as needed to suit the customer's needs, while allowing the customer and builder to ensure the results meet the rigid requirements of the Navy. [Carey]

Within the modularity concept there are three tiers of modularity - construction, technological, and operational modularity. Operational modularity stems from the need

for flexibility in mission and thus the ability to reconfigure a system on the fly, which requires "swap out" capability. The ability to change out and/or upgrade electronics throughout the lifetime of the system is known as technological modularity. These two types of modularity apply to the PBR when trying to minimize plant's operational down time due to maintenance and when upgrading machinery and electronics. Finally, in construction modularity, the system is designed and broken into separate sub systems which are constructed and tested individually before being incorporated into the entire system, which is the main focus of this PBR project. [Carey] General Dynamics Electric Boat has mastered all three of these modularization processes.

Using construction modularity for submarines was a massive deviation from the techniques used to produce submarines only a short time before. Previously, the submarine hull was assembled first and the internal systems of the submarine (electronics, consoles, etc.) were installed by through hull cuts in the top of the structure. As one can see, this procedure has many potential bottle-neck points, requires extraordinary rigging systems, takes a long time and is expensive. With the new, modular, approach each section of the submarine is constructed individually and then upon successful testing, mated and welded with its neighboring hull section. [Carey]

With the modular approach, each section of the submarine is constructed independent of the other sections, so much so that under the current submarine construction contract half of the sections for each submarine are built by GDEB at Quonset Point Rhode Island and the other half by Northrup Grumman Shipbuilding at Newport News Virginia. Each shipyard builds the same sections for each submarine and both yards use the same modular, technical, and construction techniques with consistent tolerances and testing procedures. These sections, built hundreds of miles apart from each other, are then assembled at one of the two yards on an alternating basis. In order for this submarine construction to be successful, the two corporations construct their individual sections with their own local design, under universal tolerances, while keeping the integration for final results in mind while they work to the same overall construction plan. Assuring that the hull sections match with all the component connections from section to section has been successfully demonstrated by both of these shipyards. The

above suggests that the pebble bed modularity scheme being considered for this project can work.

The tools designed for each section to properly construct, measure, and test the section's components are reused from submarine to submarine. Thus, once the first submarine, with its different sections, is successfully completed, the tools, molds, and procedures can be used repeatedly for future submarine construction. As such, the second and all subsequent submarines can be constructed with greater ease, and less time, in "cookie cutter" fashion, with extraordinarily high confidence in the integrability of the sections. [GDEB 2]

By constructing submarines in this modular fashion, and achieving the expected learning curve, GDEB has demonstrated a significant decrease in cost and time for a single submarine construction. These time and monetary savings are described in detail in section 6.1. [GDEB 1, 2, 3]

The concepts used by GDEB in modular construction of submarines can easily be transferred to the modular design and construction of the Pebble Bed Reactor. In fact, the construction of PBR power plant is simpler than that of a naval nuclear submarine in that the main focus of the modularity is in its design and construction and not in the multi-operational flexibility of a submarine. Also, the electronic system upgrades will be minor relative to the multitude of technological modularity required for the missions of submarines. As an industry leader in the area, and having been the driving force in the three tiers of modularity for submarine construction from the very beginning and throughout the entire process and throughout the lifetime of the submarines, GDEB and the corporation's vast experience, makes them more than qualified to review and provide advice on the Pebble Bed Reactor Modularity project.

As such, the successful implementation of these modularity concepts by General Dynamics Electric Boat will serve and an important background during this stage of the Pebble Bed Reactor Modularity.

3 General Plant and Modularity Engineering Concepts and How They Apply to the MPBR

Critical engineering concepts such as joining and bracing mechanisms, "best fit" attainment, and accuracy control- that are key to the success of the project are described and applied to the MPBR in this section

3.1 "Concept of Constant Flow for Best Fit"

The concept of "constant flow for best fit" is critical to the design, fabrication, and installation of the modularized energy system. This section discusses the concept in general and then lays out its implementation for our design process. In order for a modular design to be successfully assembled the concept of "constant flow for best fit" must be used at various stages in the fabrication, construction, and assembly process. [GDEB 2, 3]. The simplest description of this concept is that the flow of the work and installation is determined by using a keystone system around which all other components or space frames are connected. Depending on the types of interfaces, tolerances are established for key components that need to be met and are adjusted and measured during standardized fabrication to assure the proper "fit". Budgets for tolerances are established and maintained in the shop such that when shipped to the assembly site, there is high assurance of proper matching without extensive rework to fit.

When a system is comprised of various, segregated pieces, the pieces must fit together within some bound of tolerance. This tolerance will vary depending on the components that must come together and the means by which they will be joined. For example, when joining lower pressure, non critical components whose working fluid poses little danger, (i.e. basic atmospheric pressure water line), standard tolerances can be applied. Should this line leak at a joint, the leaked water poses little danger to surrounding personnel or environment and, while it may decrease the overall efficiency of the system, it won't render the component unusable. The joint would then be repaired as soon as practicable to get the system back on line.

Conversely, on a system that contains fluids under increased pressure, temperature, or potential hazard to the surroundings, the match up between the two parts being joined must be much more precise (tighter tolerances), as even small amounts of leakage would cause great harm to the component, the system, or the surroundings. When combining components in this system the tolerances would need to be tighter. [GDEB2,4]

Certain materials are inherently more ductile than others, however it is not wise to start bending (distorting) them to achieve alignment, as doing so puts undue stresses on the material. As such, there are other available methods to gain alignment without distortion such as using a welded joint mating piece to realign a part. Cold bending of pipe is allowed to a certain degree. In practice, only 5 degrees of bend can be added or removed from a previously bent pipe. [GDEB 2]

Finally, how the parts are joined together will also mandate tolerances to specifications. For instance, flanged joints on high pressure systems would require alignment tolerances within 0.010" to prevent leakage. Five degrees of misalignment would be allowed, on the other hand, for socket-welded joints. [GDEB 5]

3.1.2 General Best Fit Flow Procedure

In general, it is important to first identify which component(s) will serve as the "keystone" for the entire system. This component, or set of components, will need to be manufactured and located accurately. This "critical placement" requires an upfront increase in time and cost but is necessary for the overall success of construction as it decreases the time and expense of a "stick build" approach in the field. These components should be chosen because they are difficult to move or alter, and/or have multiple components attached to them and/or their placement is either decided by plant design or critical to another component.

Once the keystones have been manufactured and placed exactly where specified within agreed accountable tolerance, the other components can then be positioned. These second-level components will also have specific design considerations and may need to

be placed in their best fit location to ensure pieces mate with other pieces as required. There can be several different second-level components and also third or fourth level components that will then be positioned off of the component one level above. [GDEB 1]

Finally, after all other components have been placed and corrected for any variations, the lowest-level components are added. These components can either be flexible or prefabricated with fit up allowance built into them. They need to have some relatively significant length and at least one change in direction (bend or elbow) inherent in their design. If being fabricated, sophisticated techniques like those described in section 3.5 will be employed to determine the "as-built" conditions, or the exact variations in all degrees of freedom from the original plan. These components are critical to the success of this strategy, because they are able to adapt, and therefore allow for small imperfections during other steps in the process.

3.1.2 Concept of Flow for Best Fit Applied to MPBR

The concept of flow for best fit builds flexibility into the construction process which allows key feature locations to be redefined throughout the process and thus adjust for dimensional relationships and compensate for imperfection. For our application, there are many reasons why the tightest tolerances need to be used. The Modularized Pebble Bed Reactor (MPBR) power plant utilizes Helium gas at extremely high temperature and pressure. Also, the helium on the primary side will contain radioactivity. Thus, the minimization of leakage is important since it will not only create major inefficiencies, but will be dangerous to the environment and nearby personnel. While flanges were considered in the earlier design, due to the extremely tight tolerances required, piping and other joints will be welded, as discussed in Section 3.3 [Nayyer].

There will be two keystones for our design. The origin of our global reference system will be the Reactor Vessel outlet pipe. As discussed in Section 4.2, the ground zero position where the centerline of this pipe connects to the reactor vessel is the origin of our global reference system. Thus, its location is critical to the construction of the entire plant. Further, the position of the Reactor Vessel outlet pipe is predetermined by

the design of the reactor vessel itself and serves as the main connection between the reactor and the rest of the plant.

The next component that will be critically placed as a keystone is the inlet piping in the IHX manifold space frame. This pipe connects directly to the origin of the reference system via a straight pipe and thus serves as the keystone for the IHX section of the power plant. Since there are six IHXs that come off of this manifold it is imperative that the starting point for the placement these IHX modules is accurately placed.

The second keystone component for the MBPR are the two pipes in the power generation (secondary) side that connect, via straight piping, to the outlet of the IHX manifold. Because these interfaces are connected by a straight pipe there is little tolerance for inaccurate placement since make-up piping will not be able to compensate for any inaccuracies. As discussed in Section 5.2 the top pipe in question is part of the compressor space frame but only the pipe interface needs to be placed with tight tolerance.

Following the critical placement of these keystone components our second-level modules (IHXs, recuperator vessels) can be placed. They will be placed so as to minimize any required corrections from the IHX manifold to the IHX, and recuperator manifold to the recuperator vessels. By using various three-dimensional measuring techniques including, but not limited to, total stationing, photogrammetry, and portable coordinate measuring machines, described in detail in Section 3.5 the difference between ideal and actual positioning in each degree of freedom is calculated. These calculations are then incorporated when the make-up piping is fabricated. [GDEB 1]

For the MPBR, the make up piping that connects different manifolds may not be part of any module itself. This piping is the critical “lowest level” for our plant. Through modern technology (laser mapping an “as-built” model can be created to determine the amount of adjustment needed), the original piping plans can be modified, to meet form, fit, and function, as required to create a perfect match between components. This piping should be at least 5 feet long and at least one change in direction. [GDEB 1]

3.1.3 Causes for Exact Location Compensation

For the modularized PBR plant, there are a few reasons we would need to use the "best fit" concept to compensate for slight deviations from ideal specifications. As discussed above, one is the tolerances themselves. By allowing slight deviations, there needs to be a mechanism to compensate for such differences. For economic manufacture, the tolerances can not be set too stringently. The "best fit" approach provides the needed balance between tight tolerance and cost.

Unique to this particular method of modularity is the use of the space frame. The frame itself may become distorted as it is transported from the factory to the site. So, even if the module leaves the factory well within the allowed tolerances, once at the site there may be considerable deviation. As a result much care must be taken when transporting the modules and upon arrival at the site the ability to correct for any distortion needs to be in place and the modules need to be re-verified. [GDEB 2] Also, due to the large size of the space frames, namely the 10 m length, the frame is apt to distort and/or weep. On site, the construction team can adjust the space frame back to near its original shape using various pressing or shimming technologies.

3.2 Bracing Systems

In this design the space frame and its contents are to be considered a single "unit" that must then be aligned with the other portions of the entire assembly. While there will be some ability to slightly alter the make-up piping connections to reconcile any deviations from specifications within the allowed tolerance of +/- ½ inch, the exact positioning of this unit will serve as the first step in our "constant flow of best fit" procedure. As such, if built to plan, the space frames should line up correctly. However, due to manufacturing inconsistencies, which would be noted as out of specification, the actual position where the space frames lie may not perfectly coincide with the ideally specified location. Thus the mechanism by which these frames are attached to the ground surface must be carefully considered.

Keeping in mind that not all space frames will be constructed exactly the same since some will have bottom plates while others do not; nor will they contain the same components; nor be positioned in the same manner (i.e. some will stand tall while others lie flat); nor be attached to the same surface (some will be attached to the ground and others to other space frames; many options need to be considered.

There are several options for attaching/bracing the space frames to the ground. We will consider the benefits and detriments of each mechanism for stability, ease of use, ability to slightly adjust basic position to enable the first step of best fit, and ease of unit removal for repair or upgrade or replacement. Each design considers if the mounting holes should be permanent (and thus the adjustability be built into the frame) or if the mounting holes will be adjustable and the frame's bracing mechanism permanent. Again, no one design is perfect for every frame, so there will be different mechanisms for each particular frame.

3.2.1 Space Frame Design A

In this design, alignment anchor bolts will placed in the ground or mounting surface will be pre-drilled and therefore permanent. The ability to "best fit" the module will require that the unit itself have the ability to allow for adjustments. Standard on-site tolerance [GDEB 4] is +/- ½ inch of the specified location in either direction. The permanent ground anchor bolts will be at placed key locations (the center of each section of the frame). The placement of the space frame holes will depend on the actual field bolt locations. At this ideal position on the frame a "bulls eyes" like marking can be placed.

The alignment anchor bolt locations will be precisely measured and drilled in the field. The frame itself will also have precise holes drilled in it for connecting to the alignment bolts. Additionally, there will be pre-drilled holes in the space frame to allow for additional anchorage into the ground for seismic and structural support, which do not need to be precisely aligned.

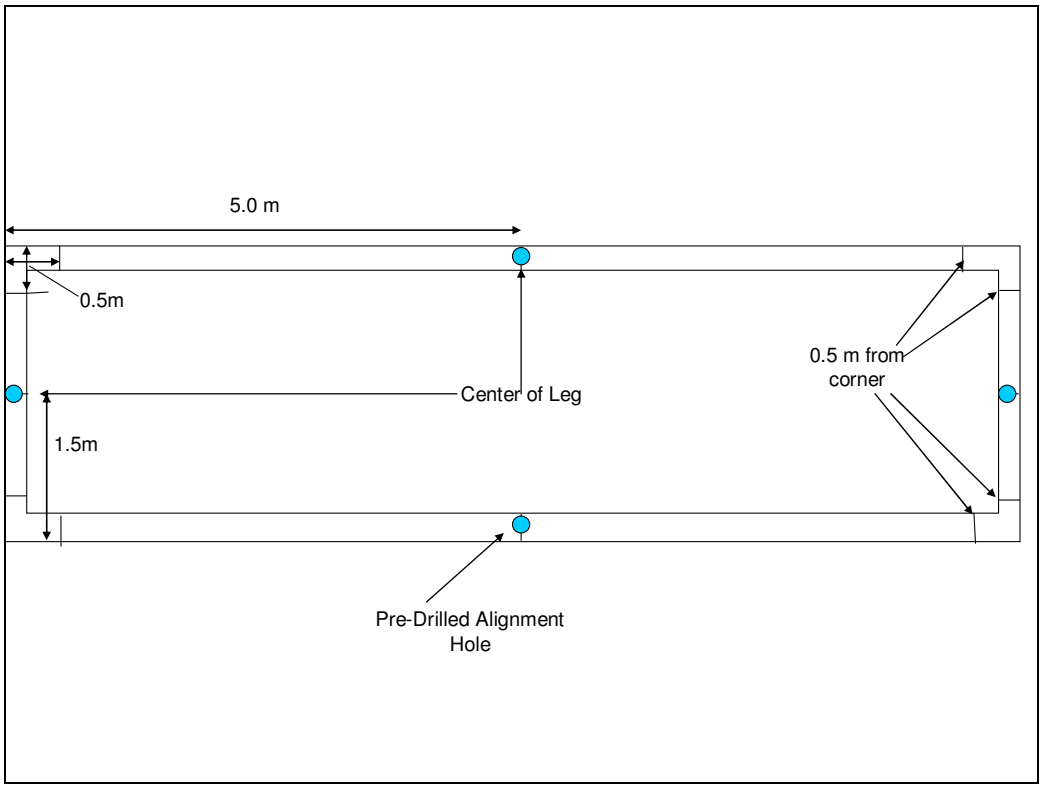

Figure 12: Space Frame Design A, Showing the Pre-Drilled Alignment Holes and Reference Marks (2.5 X10 m Manifold Frame shown)

Correct application of this design will rely heavily on the ability to correctly determine where the holes for the mounting bolts should be. To aide in this process several 3-D measuring technologies are available, including the use of photogrammetry and laser, as outlined in section 3.5. This technology helps alleviate the difficulty of this procedure. This design does, however, allow for the easy replacement of modules, as the same process can be done on the new frame, using the already existing holes. In modules that will make use of bottom plates for support of components, the bulls-eyes can be placed on the plate itself. All other procedural steps remain the same. Since the frames' placement will be nearly exact, Frame A will be used for the keystone frames.

3.2.2 Space Frame Design B

Design B does not require alignment bolt-hole locations. Instead, to maximize placement flexibility, bolt holes will be drilled in and bulls-eye markings placed on the the frame in the shop.

The Bulls-eyes will be located in the center of each leg of the frame and used to properly align the frame with its interfacing components. Once on site, the frame will be placed using the bulls-eyes and the pre-drilled holes will be used to drill bolts into the ground. The number of pre-drilled holes will be determined by structural support needs.

This procedure is much simpler than design A and requires much less use of sophisticated measuring technologies. Design B will be used for most of the space frames.

3.2.3 Space Frame Design C

In design C there will be no bolt holes, but rather brackets will go over the frame and be attached to either the ground or other space frame. Such a design will allow for slight adjustment in one direction. For alignment purposes, either bulls-eyes or reference marks will used.

3.2.4 Space Frame Design D

Some space frames may allow for more flexibility in placement. As such, slotted holes be used for more flexible bolting (to either other space frames or structure).

3.2.5 Bracing for Modules

In order to brace the modules in a manner that is most appropriate for the function and location, the ground bracing system will consist of steel plates that are pre-drilled for space frame connector bolts that will be embedded in the concrete floor. These plates will be slightly larger than the bottom of the space frame. During the space frame outfitting process, the same three dimension measuring techniques described in section 3.5 will be used to accurately place the bolt holes in the frame. Additionally, eccentric bushings – which are able to adjust slightly- can be used in the base plate.

3.3 Joining Systems

This section considers the benefits, drawbacks, and applications of welds and flanges. Their use within the MPBR is described.

3.3.1 Welding

Welding joins materials, usually metals or plastics, directly by melting the work pieces and adding filler material to form a weld puddle. It is then cooled to form a strong joint. There are several methods of welding, including gas metal arc welding, submerged arc welding, flux cored arc welding and electroslag welding which are all semi-automatic or automatic. The currently most used process of shielded metal arc welding is manual. Automatic welding machines are often used for welding in certain situations. [Nayyar] Welding provides a "permanent" joint. In order to remove a component that is joined by welds, the pipe/component must be cut through, the component removed, replaced, and new welds made after preparing the joining surfaces.

The quality of a weld, and therefore the joint, is determined by the strength of the weld and the material(s) it joins. Non-destructive testing (NDT) can be used to test the strength of a weld. For construction purposes, NDT methods such as magnetic particle, liquid penetrant, ultrasonic, and/or radiographic inspection, are used. These NDT methods, which inspect not only the weld proper but also the heat affected zone (HAZ) are invoked in design and manufacturing drawings and specifications to ensure that the welds and surrounding base metal are defect-free. Inspection acceptance criteria are generally promulgated in the welding codes and specifications applicable to the specific NDT method and end-use application of the part being manufactured. It must be kept in mind however, that commonly specified NDT methods do not measure levels of residual stresses and distortion associated with the various welding processes. [Nayyar] These items are accommodated in the design phase, using either empirical data or specific engineering analyses. Because of the great skill involved in successful welding, skilled welders are paid a premium wage. [GDEB 2] Additionally, for helium systems extensive leak testing may be required of all joints.

3.3.2 Flanges

Flanges are internal or external rib(s) or rim(s) used for strength and for joining components in a system. [Nayyar] For pressurized systems it is not uncommon to use an O-ring with the mechanically attached (bolted) flange to ensure a seal between the

components. [Nayyar]. They are a round shaped loop of elastomer or metal designed to be seated in a groove and compressed during assembly to create a seal at the interface of the two parts. Generally speaking, O-rings are relatively inexpensive, easy to use and can withstand fluids with pressures into the thousands of psi.

Because they do not permanently attach the parts like welding, mechanically attached flanges offer the ability for easy removal and/or exchanging of a component. This is highly desirable for the PBR modular power plant, as the ability to exchange, upgrade or service components while the plant is operational is a key factor in its design. The original idea, published by Berte in his thesis makes use of flanges with O-rings to form the seal between the components [Berte], but this has been challenged based on discussions with a leader in modular construction. For helium systems to ensure a leak tight connection "omega" seal welds will be needed for all flanged joints.

3.3.3 Best Joining Mechanism for the Modularized PBR

General Dynamics Electric Boat (GDEB), a leader in modular design and construction, has used welded joints extensively for their successful modular design and manufacturing programs [GD-weld]. The reasons for their choice of welded systems which are more costly and time consuming joining application should the component need to be removed are described as follows:

In many applications, flanged joints are more difficult to align during initial fit-up. For some specific applications, most notably with gases like helium, the potential for leakage is greater than with welded joints. [GDEB 5] Properly aligning gaskets and O-rings is critical, but may prove difficult and time consuming to achieve. The bolts on flanges require some degree of torque, which can be difficult to maintain. Additionally, mechanical fasteners can relax (loosen) over time due to the loadings associated with thermal and pressure transients. As such, mechanical joints require monitoring and re-torquing over their life cycle.. This requires additional labor hours relative to welded joints and increases the maintenance requirements for the specific application. On the other hand, weld joints are put together once and released for operation after specified

NDT is performed and has proven the integrity of the joint. By doing it this way, the joint requires no further attention. [GDEB 5]

The following summarizes why welds should be used for the PBR system:

Flange joints should only be used when there is a need to have the ability to remove a component or to gain access to a particular area, but flanged joints in a helium gas system will require seal welding to prevent leakage from the joints. A requirement for seal welded flanges removes a lot of the advantages of having a flanges joint especially since seal welds are typically much more expensive (due to time) than regular welds. Furthermore, the increased use of automation and off-site modular construction in a controlled factory environment ultimately improves product quality and decreases the labor hours, and hence premium pay, required for on-site work evolutions. The question of just how often it is anticipated that there will be a need to remove an installed component in the field is important. It is judged that the frequency of such removal will be low enough that welding would be an acceptable approach when combined with the difficulty of matching flanged components.

Thus, in an effort to optimize installation and maintenance labor hours over the life cycle of the plant, thereby reducing the overall cost while ensuring the highest possible system quality and operational safety, the design proposed by Marc Berte will be modified to use welds. These welds will be made using automated and semi-automated welding techniques as much as possible, and time to conduct NDT and ensuring adherence to specification will be reflected in the overall construction timeline.

3.4 Support Systems

An important aspect in space frame design is how the equipment in the space frame is supported. According to the United States Nuclear Regulatory Commission, (USNRC) “piping must be supported to prevent its weight from being transferred to attached equipment.” [USNRC] This can be accomplished by using several different types of supports, including adjustable hangers, variable spring hangers, constant

supports, roller stand supports, and snubbers. This section will describe each type of support and where they should be used throughout the plant.

3.4.1 Pipe Hangers

In general, pipe hangers prevent pipes from sagging while allowing for slight pipe movement due to thermal expansion and contraction, along with vibration. They must carry the weight of the pipe, the weight of the fluid in the pipe, and the pipe's fittings, insulation, and valves. [USNRC]

3.4.2 Rigid Hangers

Rigid hangers (also known as adjustable hangers) do not allow for any vertical movement and support the dead weight. This can be accomplished using a simple strap and clamp. If horizontal motion is also a factor, a roller is used if some horizontal movement is expected [USNRC]. Figure 13 below shows adjustable hangers

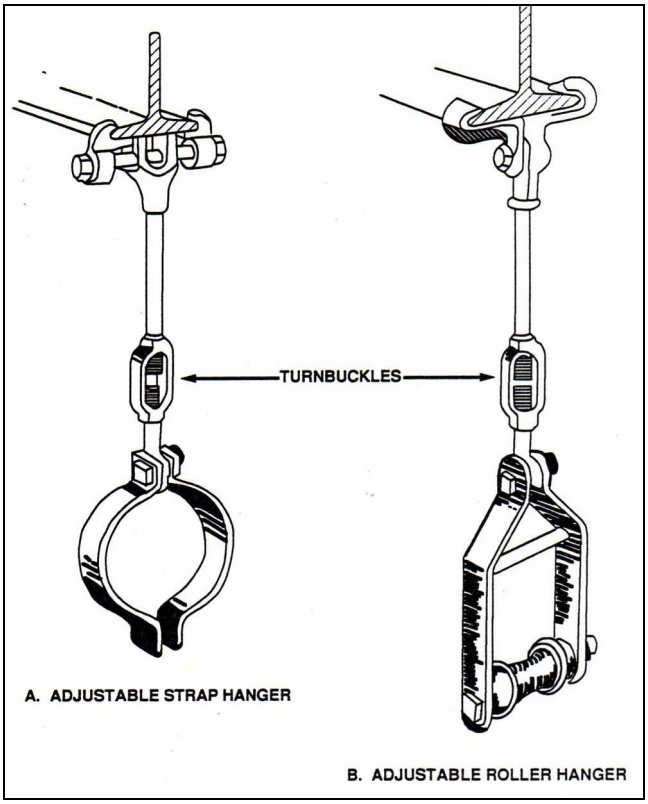

Figure 13: Common Adjustable/ Rigid Hangers [USNRC]

3.4.3 Variable Spring Hangers

Variable spring hangers allow the piping to move up and down without a sudden load distribution disruption. They also support equipment that may move slightly in the horizontal plane due to the movement of attached equipment or neighboring piping, like a thermal expansion of a vertical pipe run followed by a 90 degree bend, followed by a horizontal run. [USNRC] As such, it is best used on equipment that may be subjected to slight vertical movements, and has 90 degree bend geometries involved, such as the make up piping for the PBR plant in this design.

These hangers also provide a cushion for the piping system, and, as such, their springs are subject to becoming compressed. Figure 14 shows Variable Spring Hangers.

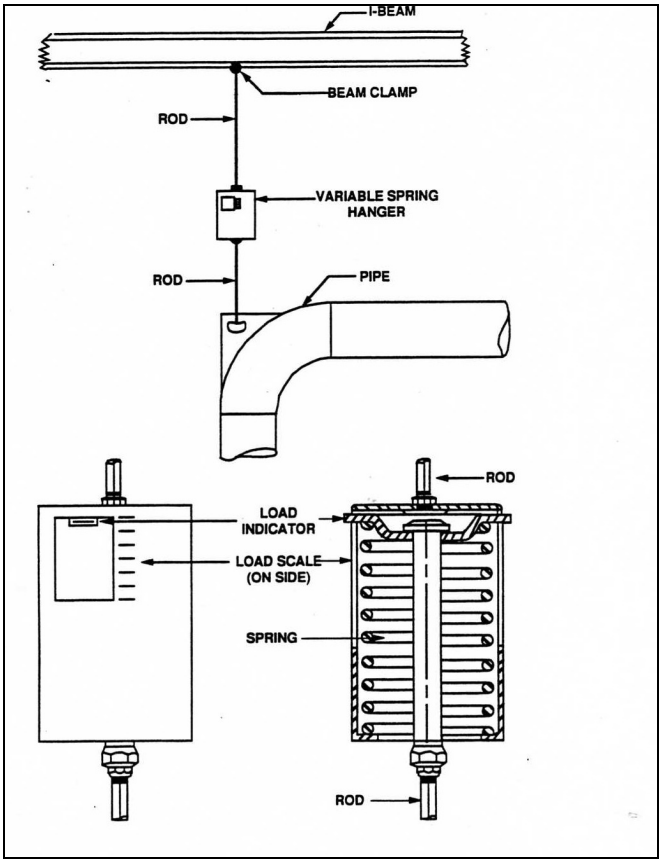

Figure 14: Variable Spring Hanger [USNRC]

3.4.4 Constant Supports

With constant supports, a coiled, helical spring moves as the pipe moves to provide support to systems where the anticipated vertical movement is significant. These supports are adjusted to support a specific load while in the factory, but, through tightening or loosening the spring tension, the factory instated compression can be readjusted. During the operation of the plant, care must be taken to ensure these springs do not become fully compressed or that the load indicated on the load meter does not exceed the predetermined limit. [USNRC] Constant supports are used in systems where the anticipated vertical movement is significant. Figure 15 shows constant supports.

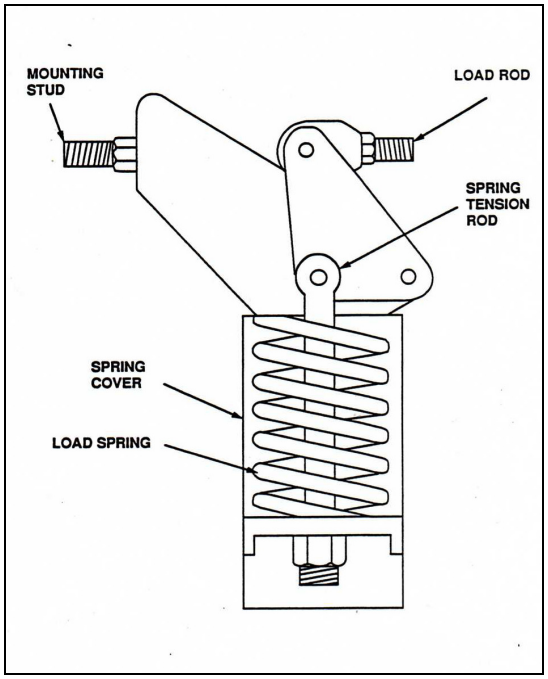

Figure 15: Constant Support [USNRC]

3.4.5 Roller Stand Supports

Roller stand supports may be adjustable - four adjustable screws are adjusted to raise or lower the stand to match the position of the pipe - or nonadjustable. These

supports allow the pipe run to have unlimited horizontal movement and are therefore used for long pipe runs in which expansion and contraction is predicted. [USNRC] For the MPBR discussed in this thesis, roller stand supports will be used in the upper and lower IHX manifold modules, and installed as part of the space frame at the fabrication origin. For the bottom manifold, they will be attached to the bottom plate, and for the upper manifold, they will be installed along each of the three horizontal supports described in more detail in section 5.1. Our design will use the nonadjustable roller stand supports for the bottom manifold since this is the keystone of our design and should not require any further adjustment, while the upper manifold will utilize the adjustable type of roller stand supports, as some minor adjustments may need to be made on location during the construction phase. Both types of roller stand supports are shown in Figure 13.

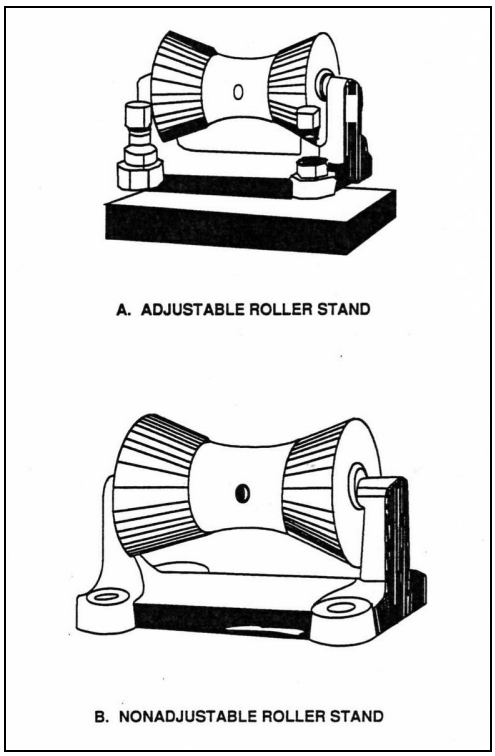

Figure 16: Two Types of Roller Stands [USNRC]

3.4.6 Snubbers

Snubbers are designed to allow gradual movement for thermal growth while resisting sudden pipe movements from seismic events, pipe whip, vibration or shock. Snubbers are a special application of supports that are key to any nuclear plant design, as there are many systems that must be able to survive a seismic event but be allowed to expand and contract. Most control the pipe in two directions. [USNRC]

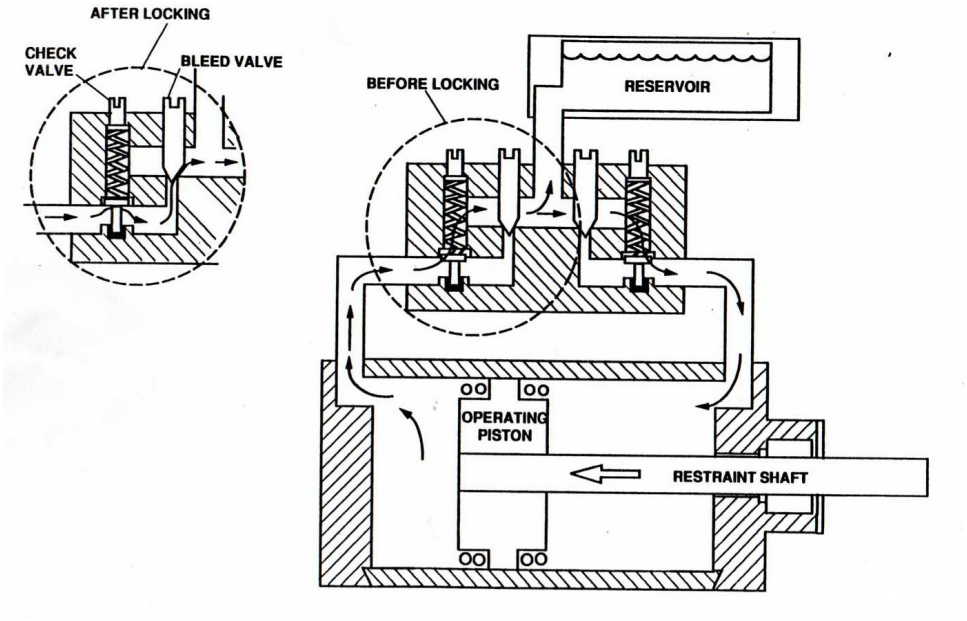

Figure 17: Basic Arrangement of a Hydraulic Snubber [USNRC]

Hydraulic snubbers, shown in Figure 17 are the most commonly used type of snubbers. A piston in the cylinder of the snubber is driven by pipe movement, which then forces hydraulic fluid to move past a spring-loaded check valve. When the movement is due to thermal expansion and contraction, the fluid's movement is not limited by the check valve, since the pipe movement is relatively small. However, when the movement is large and sudden- as in an earthquake- the check valve will be seated by the pressure and a "hydraulic lock" will be placed on the operating piston. Normal operation of the snubber results once the hydraulic lock is slowly released by a small bleed valve.

Although snubbers allow for pipe movement in two directions while resisting sudden movement during a seismic event, failure of snubbers is a risk. Failures occur in

snubber systems for many reasons, including failed seals and O-rings which destroy the hydraulic action; cracked reservoirs and loose fittings cause hydraulic fluid loss; contaminated hydraulic fluid affect clearances and bleed rates; and extreme temperatures can cause internal damage. These issues, while they only slightly impact normal plant operations, can be devastating in the event of an earthquake.[USNRC] Snubbers will be placed throughout the PBR plant, added after the main space frame components are placed in the module, and attached to the inside of the frame. For piping outside of any single module, snubbers will be added from the horizontal support bars described in section 5.

Berte, in his earlier work, performed a thermal stress analysis to allow for support of the piping systems and components to allow for thermal expansion of the components in the space frames. [Berte] He did not, nor does this thesis address how these supports will be mounted on the space frames. However the intent is to have all supports for all the components in each space frame mounted on the space frame using additional cross supports and bracing as needed to provide both structural support, accommodate thermal expansion and deal with design basis seismic events.

3.5 Accuracy Control

This section discusses how accuracy control is used to support modular design and construction. In addition it will discuss accuracy control procedures, and some of the techniques used to achieve acceptable accuracy.

According to General Dynamics Electric Boat (GDEB), accuracy control is defined as "measuring selected dimensions during manufacture, assembly and outfitting to allow adjustments to assure the final product meets drawing requirements, readily fit to mating parts and achieves system functional needs". The goal of accuracy control is to reduce manufacturing, outfitting and assembly costs while improving the quality of the product and minimizing rework. [GDEB 4]

With modular construction, individual modules, complete with various components, are built and assembled at various locations and then shipped to the

construction site where they are integrated to form the complete plant. In order for this to occur, the space frames, along with the components they house need to be manufactured and placed accurately (within plan tolerance) to ensure their interfaces easily mate with their counterparts. In short, there needs to be an extensive system of accuracy control in place for modular construction to be successful. GDEB has an extensive and unique accuracy control organization, which has proven critical to their success in modular construction of submarines. While each organization will have its own accuracy control program, which may be very similar, the methods and techniques used by GDEB have proven effective and are discussed in this section. Also included in this section are descriptions of various three-dimensional measuring techniques and equipment.

3.5.1 A Proven Method for Accuracy Control

There are four major steps in the accuracy control process. First, the measurement requirements need to be defined. Second, these requirements need to be implemented and accomplished. Then the collected measurements need to be evaluated and finally, the process is adjusted (Lessons Learned Incorporated) accordingly, as required to assure mating of all components and surfaces. [GDEB 4]

During the first step, critical measurement requirements are identified based on final tolerance plan requirements. This includes deciding on in-process, budgeted tolerances for general equipment and identifying which equipment requires tighter tolerances. These components are usually critical to the system or layout of the system. The intent of in-process budgeted tolerances is to identify potential problems earlier in the construction process and take steps to prevent them from becoming larger more costly problems. The “key” for layout should be to minimize the tight tolerances whenever possible so as not to adversely increase costs and schedule.. The final tolerance plan is reviewed in order to decide how to best back-budget the tolerances. Also during this step, work orders are developed from an electronic database to manufacture the components. The Accuracy Control requirements and data sheets are created and added to the work packages and training conducted. [GDEB 4]

Next, during the implementation of the measurement requirements stage, the requirements list is published and reviewed with the trades. Tolerance adherence occurs during this step. Measurements are made using various methods from standard mechanical and optical tools to three-dimensional measuring techniques (such as laser trackers, photogrammetry, total stations, laser scanners, and portable coordinate measuring machines) and reported to an electronic database allowing for post survey three-dimensional modeling and analysis. These 3D measuring techniques are described in detail later in this section. [GDEB 4]

During the third stage, the collected measurements are evaluated by an Accuracy Control Coordinator. If the measurement exceeds the required tolerance on the data sheet, an Out of Tolerance Report (OTAR) is generated. For requirements that are met using three-dimensional measuring, a 3D report is generated and 3D modeling/ dimensional analysis occurs. The data is reviewed and if all of the Accuracy Control requirements associated with the work orders are within tolerance, they are closed. If the data shows an out of tolerance condition, it is reported and then reviewed for adjudication and correction as needed [GDEB 4]

Finally, the process is adjusted as required. The results are reviewed by the Accuracy Control team and then again with the trades. The procedure is then revised to incorporate any lessons learned. [GDEB 4] Through these four steps the continuous process of accuracy control is conducted, evaluated and improved, which allows for more precise alignment. [GDEB 4]

3.5.2 Tools and Techniques of 3D Measuring

There are several tools employed for 3D measuring. This section will briefly describe photogrammetry, laser trackers, a total station, portable coordinate measuring machines, and other standard optical tools. It will outline the principles of each technique, and their manufacturer's advertised achievable accuracies. Due to many variables, including the measuring environment, the component being evaluated, software used, and human error, the actual achievable accuracy may be different.

3.5.2.1 Standard Optical Tooling Equipment

The most basic accuracy control equipment falls under the category of standard optical tooling. These include familiar tools such as levels, alignment telescopes, optical levels, and theodolites like those used by land surveyors. These tools are only accurate to +/- 1/32 inch to 1/16 inch, which is satisfactory for certain purposes such as weep or sag in a plate, but may be limited in the world of highly accurate modular construction. [Brunson]

3.5.2.2 Total Station

Another tool for 3-dimensional measuring is the total station. It is a combination of electronic transit and electronic distance measuring device (EDM) in which one can determine angles and distances from which the actual X, Y, Z locations can be calculated. These points are determined in absolute terms.

A Total Station Theodolite is made up of a basic telescope with cross-hairs for target sighting. The angle of inclination and rotational angle of the telescope is found by attaching the telescope to scales and aiming at the target by rotating the telescope. A digital read-out of the angles of inclination is provided by the electronic transit. As a result, errors caused by inaccurate recording and interpolation between scale marks are minimized and thus the unit is more accurate. Also, since the read-out is continuous the angles can be checked at any time during the process. Accuracy of total station machines is around 25/1000 (.025) inches. [Tsukahara] Downfalls of the total station include is relatively slow pace and that visual sighting to the reflective targets is required.

3.5.2.3 Portable Coordinate Measuring Machines (PCMMs)

Portable Coordinate Measuring Machines are simply portable versions of coordinate measuring systems. This creates the ability to move the measuring machine to the equipment, thereby eliminating the sometimes cumbersome task of moving the component to the measuring machine. [DeFoor]

These units are made up of four major pieces including an articulated six-axis digitizing arm, control arm unit, and contact and non-contact measurement software. Coordinating measuring machines are able to measure the X, Y, and Z values within 5/1000 (0.005) inch. Using a pre-established coordinate system, they are able to produce real time data for small volumes. [DeFoor] The downside to PCMMs is that they are limited to the size of the object that they can measure.

3.5.2.4 Laser Trackers

Even more accurate than PCMMs are laser trackers. They are accurate to within +/-1/1000 (.001) inch. Like most 3-dimensional measuring tools, it utilizes triangulation to achieve its result. Laser tracker can be used to measure at close distances or as far as 35 meters away. [Bridges]

The laser tracker sends a laser beam to a retroreflective target that is held against a target to be measured. The reflected light retraces its path and re-enters the device at the same position it left. Two angles and a distance are measured and, via triangulation, the exact location of the target calculated. [Bridges] While laser trackers are extremely accurate, they require a stable platform to be accurate. Additionally, the need for the laser beam to be unbroken can cause work in the surrounding areas to halt, thus increasing the schedule and overall cost of the project. [Bridges]

3.5.2.5 Photogrammetry

With the same 1/1000 (.001) inch accuracy of the laser trackers, and without the stability and laser beam requirements, photogrammetry offers an excellent alternative. Also, a large volume of data can be quickly gathered. [Ganci and Handley] Photogrammetry was developed in the mid 1800s and, while it is the oldest remote sensing technology, the advances in digital photography have significantly improved its accuracy.

During the process, at least two photographs of the image are taken from different positions and common points on the pictures identified. A line of sight is then

constructed from the camera to the object. This triangulation (intersection of the rays) determined the 3D location of the point of interest. [Ganci and Handley]

3.5.3 Summary of Accuracy Control

The tools described above are available to all industries and each can be used for different applications. While General Dynamics Electric Boat already has a system which defines which tools to use for what components, it is ultimately up to the industry to utilize the above tools and methods as it sees fit to ensure needed accuracy control.

By using these various accuracy control methods, the exact three dimensional location of interfacing components of each module can be determined for tolerance adhesion and location. Once this information is known, the module can be placed to ensure the interfaces align and/or that they within the pre-determined tolerance so that either the pre-fabricated make-up piping is sufficient to join the parts or if out of the allowed tolerances the collected information is used to adjust the make-up piping fabrication to ensure components align. In summary, accuracy control technology is sufficiently developed and integrated with visualization software to accurately position the space frames and internal components to assure that once shipped they will align in the field with minimum rework.

4 Modularized Pebble Bed Reactor Fabrication and Assembly

To apply these techniques to the manufacture of space frames containing components and piping systems as described above, a reference system for each individual module, and the entire plant itself is required. This section outlines the module frames and reference systems for dictating placement of cross connecting pipes and components, placement of supports for these pieces, and the frames themselves in the overall plant configuration.

4.1 MPBR Space Frame

To enable transport by truck or train, the basic power plant frame will consist of a six face module that is 2.5 m wide and 3m long and 10 m in high. [Berte] The frame will remain as open as possible, with plates being added to the bottom or sides or top as required for stability or component support. The open structure allows for the easiest access to components and allows for maximum atmospheric cooling. The determination of steel plate usage will depend on the equipment housed in the frame. Supports will be installed directly from these faces and from the frames themselves, or from externally supported frames. While plates allow for easy "stamping" of exactly where components are to match up/ go through to meet their mate in the neighboring frame, the frames structure can likewise be marked with reference lines to indicate where major components should lie.

To aid in the proper placement of components that need to align with other module components or make up piping (see section 5.3) and the proper alignment of frames with one another (when applicable) and/or support bars (where applicable), every frame will have standard markings 0.5 meters in from each of the corners and at the leg's centerpoint. Shown on Figures 19-21 show the standard space frame markings.

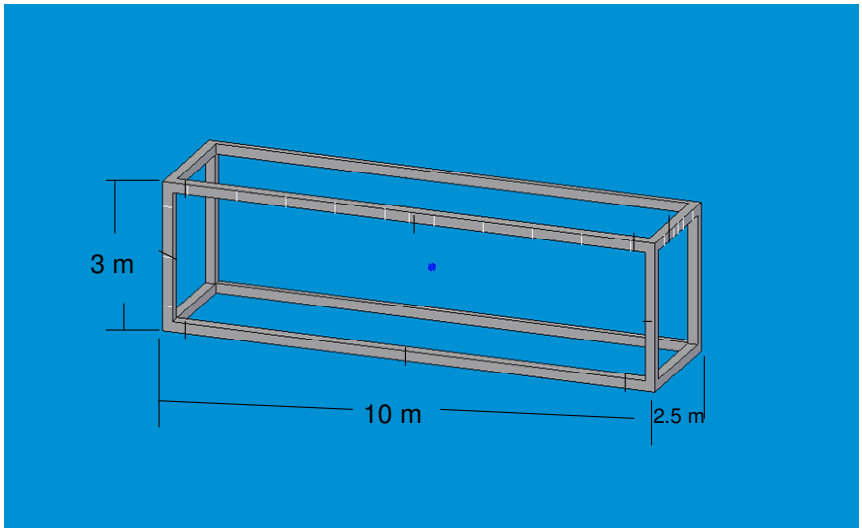

Figure 18: Space Frame with Reference Marks (Black Dashes on Frame):

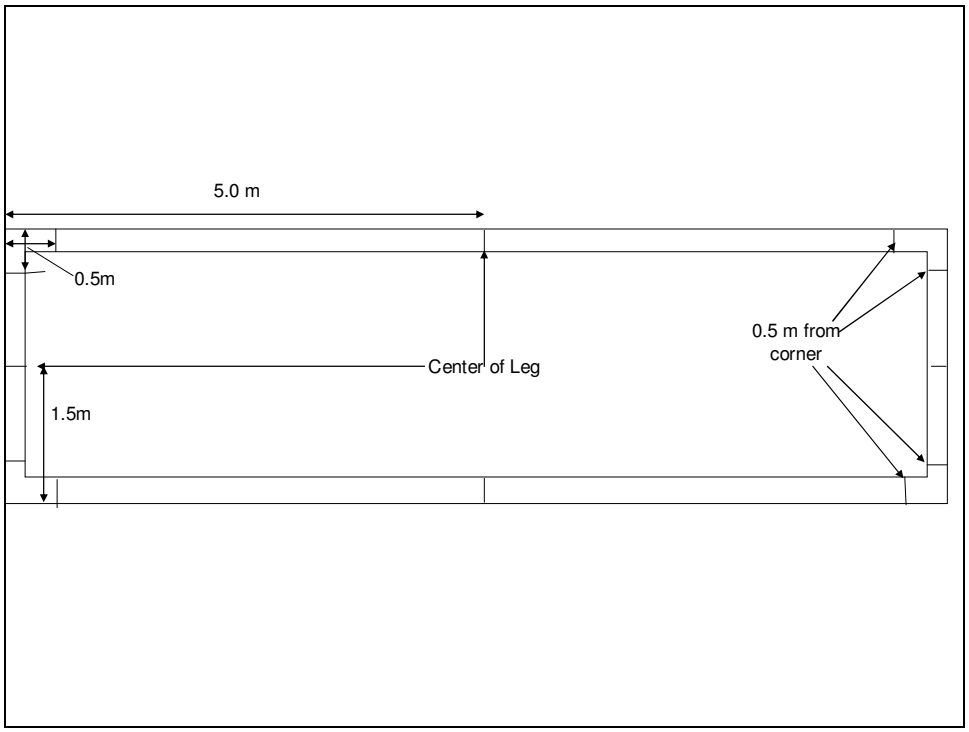

Figure 19: 3 X10 m Portions of the Space Frame With Reference Marks

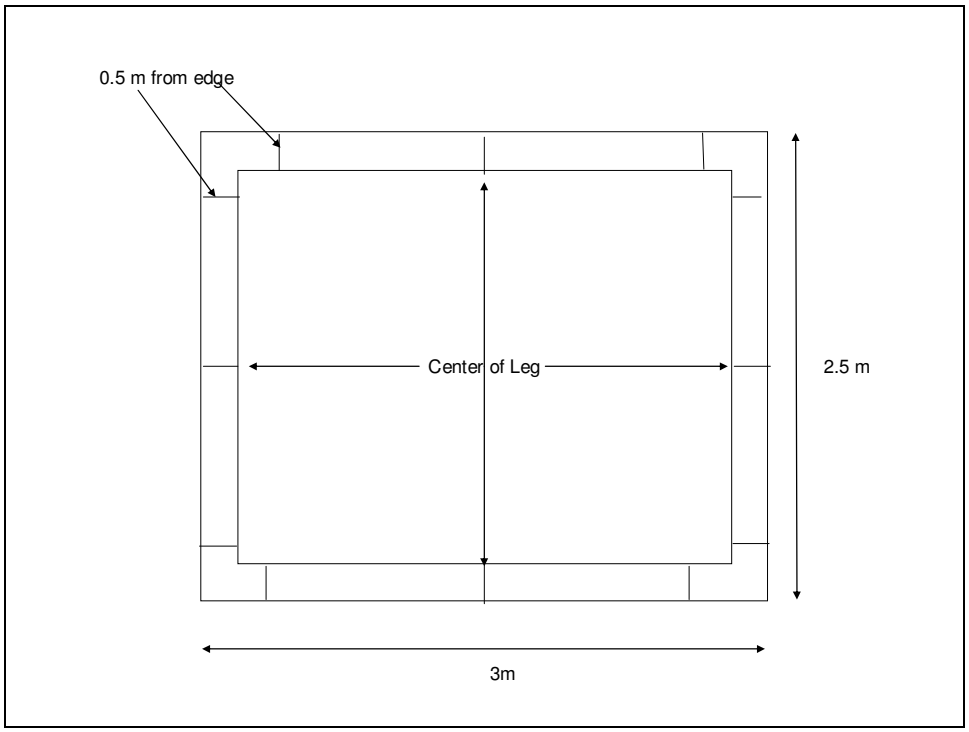

Figure 20: Detailed 2.5X3.0m Section of Space Frame with Reference Marks

The 10 meter face has markings 0.5 meters from the edges, along with markings at 1 meter increments until the center, where the +/- 4.5m and dead center 0.5m positions are all marked. The 2.5 m frame has markings at .5 from the edge, as well as 0.5 meter increments through out the entire side. These markings provide for easy alignment when assembling the plant itself. Additionally, these markings will create and inherently default position for the placement of bolts. See section on Bracing Systems (Section 3.2).

When frames are to be connected to one another, they will be connected by bolts on at least one position per frame side that is connected to another. The bolts will normally be placed on the reference marks located 0.5 meters from the edge, but may need to be relocated or have additional bolts used depending on the equipment inside the frame, the frames' orientation, and the bolts' ability to be removed for repair. The number of additional bolts will be determined by the seismic and structural stress analysis of the integrated space frame design. Figure 22 shows how the space frames are connected.

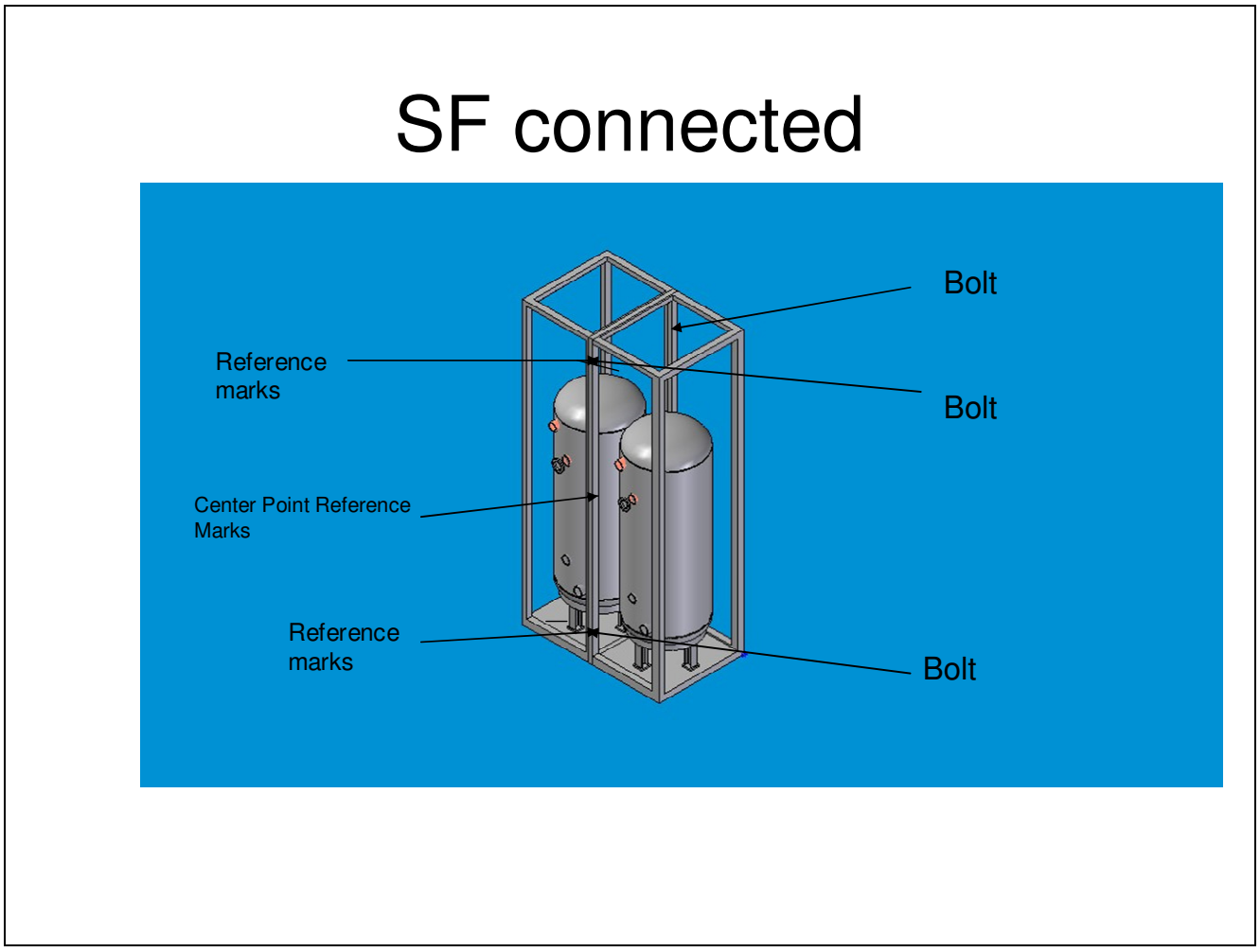

Figure 21: Example Drawing of How Two Space Frames Would be Joined.

This Drawing Shows Three Reference Marks Appropriately Matched and Where Bolts Will be Placed for Three of Four Placements (the Fourth Location Cannot be seen in this Drawing due to the Equipment in the Frames)

4.2 MPBR Global and Local Reference Systems

The reactor vessel has been modularized into five sections: two main cylindrical sections, a lower cylindrical section, a top cap, and a bottom cap. It will sit upon supports and have an outlet pipe at a 90 degree angle at the centerline of the vessel in the bottom section. This outlet pipe will be the starting point in designing the reference grid from which all locations of space frames and associated connection will be determined.

4.2.1 Global Reference Systems

The global reference system is a three dimensional grid emanating from the reactor vessel point of origin. Within this grid, the space frames will be located and the corresponding connecting pieces will be positioned within the space frame grid system which is integral to the global reference system. The starting reference, point, or origin of the system, will be on "ground" level, directly below where the centerline of where the Reactor Vessel Outlet Pipe meets space frame number one (the lower IHX manifold). This origin was chosen because it is where the reactor vessel outlet pipe meets the face of the space frame which will be a key, fixed, position during construction. As a result, there will be no negative ordinates in the vertical axis and negative X values will only occur with the small amount of piping between the space frame and Reactor Vessel and the Reactor Vessel itself (which was not the focus of this thesis) Figures 23 and 24 show the Z-X and X-Y Reference Planes.

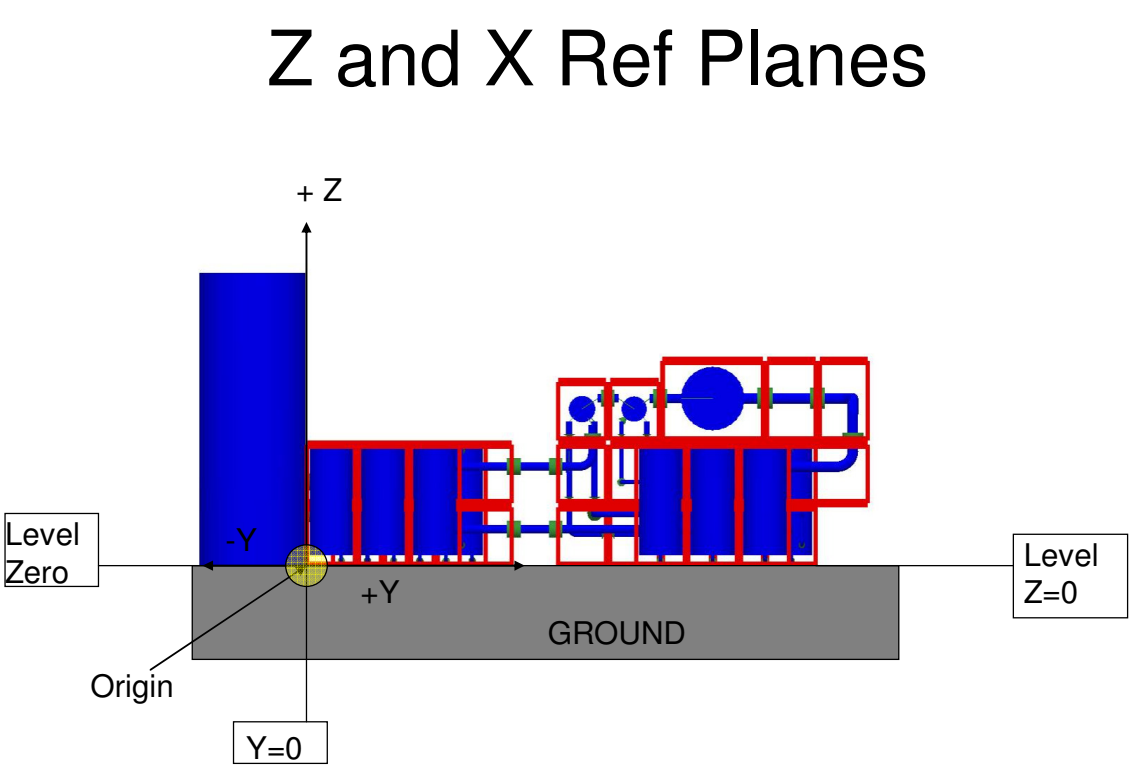

Figure 22: The Y Z Reference System. The Origin is Shown by the Yellow- Highlighted Circle. [Berte and Hanlon]

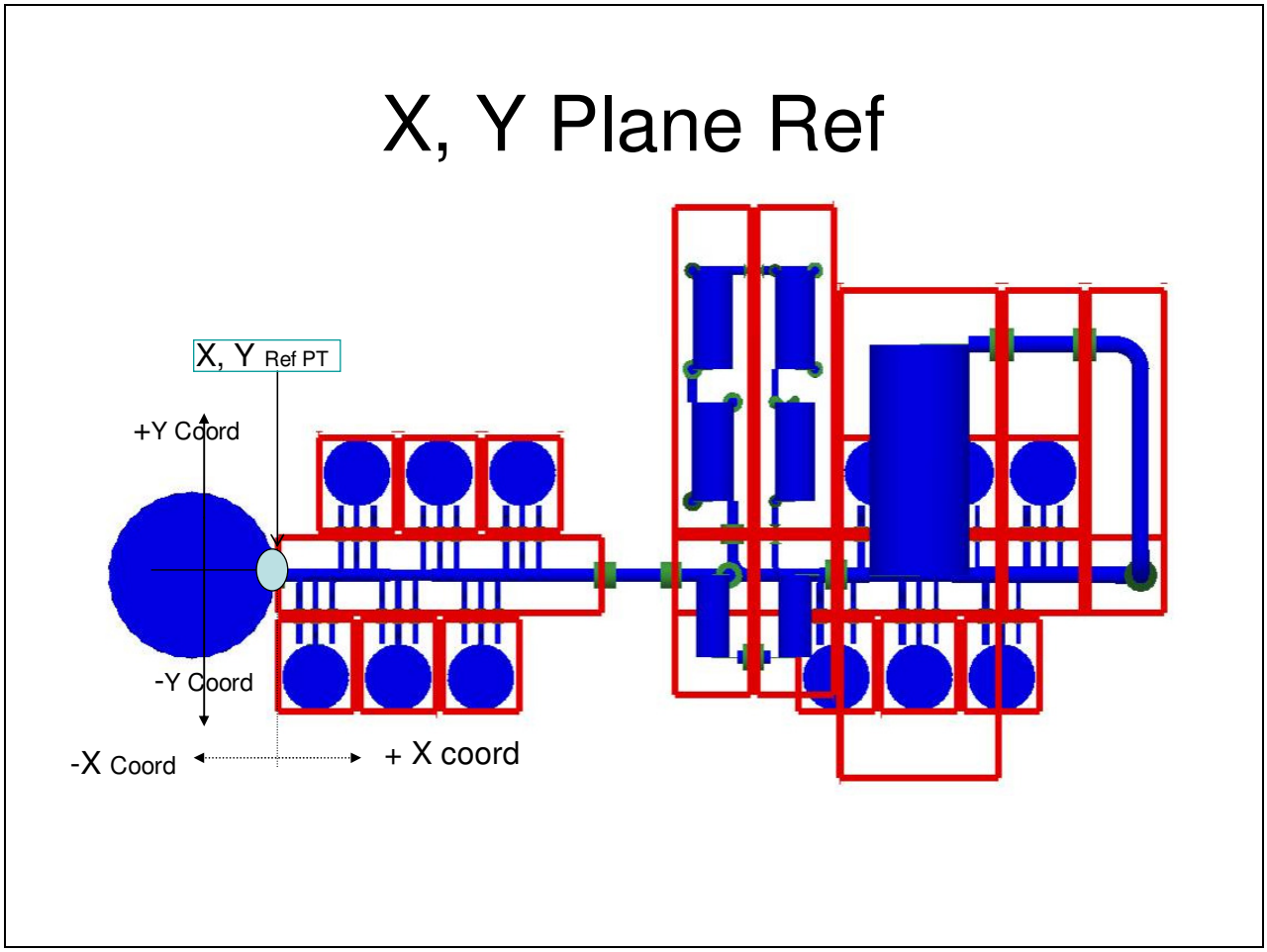

Figure 23 IHX Side Global Reference System- Top Down View. The Origin for the X,Y axis is noted as "X,Y Ref PT" and Highlighted by the Light Blue Sphere [Berte and Hanlon]

From this starting point, the position of the corners of all of the frames can be assigned, and serve as the basic reference system for the entire power plant. Within each frame, the location of interfacing components and supports can be located and manufactured relative to overall plant reference system. For example, the bottom plate of one module might have corner ordinates of (2.5,0,0), (5.0,0,0), (5,5,0), and (2.5, 2.5,0) with all measurements in meters and the coordinates x, y, and z referring to the horizontal length, horizontal width, and vertical height, respectively. Within that frame a support

may need to be hung from the top in the center of the frame. Thus the position of this support will be (1.25, 1.5, 5) in the frames' local system and (3.75, 1.25, 10) in the power plant reference system.

Since there is a thick shield wall between the reactor cavity containing the reactor vessel and Intermediate Heat Exchangers and the power conversion portion of the plant, a separate global origin is used for the power conversion side. Its Y axis origin will be determined by the exit location of the secondary piping in the IHX section. Even with thermal expansion, this will remain relatively stable, given that it will be surrounded by thick wall, thus limiting its movement in two directions.

Similar to the global reference system for the IHX section, the global reference system for the power conversion side will be located at the ground level of the centerline of where the piping meets the space frame.

4.2.2 Local Reference Systems

One key to the accurate and timely construction of any modular system is the ability to accurately construct the base modules. Each module, while needing to ultimately fit into the greater global system, components must first be accurately placed within its specific module. In order to accomplish this, the local axial system must be in a location of minimal distortion. With the advent of such technology such as photogrammetry and laser enhanced positioning and control systems for mechanical engineering, this is possible to +/- ¼ inch [GDEB 4]. In order to normalize these tolerances with possible deformations, the placement of the local axis is critical. Since a point in space is not subject to any mechanical issues, the most logical place for the placement of any local system is the center of the designed module. Thus, all local coordinates will be described from the center of the space frame (i.e. (0,0,0) locally is equal to (2.5, 3.0, 5.0) from a corner of frame).

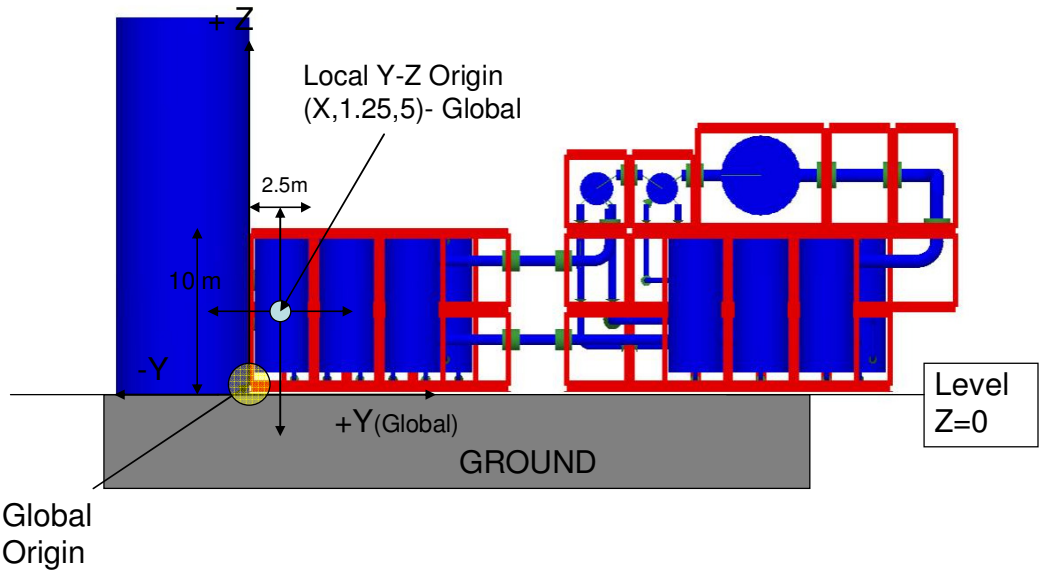

Figure 24: How the Global and Local Reference Systems Relate. The Global Origin is Shown in Yellow. The Space Frame's Local System Origin is Shown in Light Blue. [Berte and Hanlon]

In determining the coordinates for all pieces of interest, one cannot simply pick a point in space. Rather, the frames are designed with their components related to an easy to define corner, like one on the ground near a corner, and then the local coordinate system is calculated. Due to the advances in tolerance technology (see section 3.5) the ability to build to design specifications is amazingly high, so interfacing components can be located very close to their designated positions. [GDEB 2]

4.2.3 Keystone

The keystone for the plant outside of the reactor vessel will be the IHX manifold. This piece will be 10 m length, 2.5 m wide and 3 m tall and lay with the 10 m length portion on the ground. This manifold holds the pipe being used for the centerline and has two of the four pipes that connect 6 nearly identical IHX frames attached to it. From the manifold's exit, the power conversion side of the plant begins.

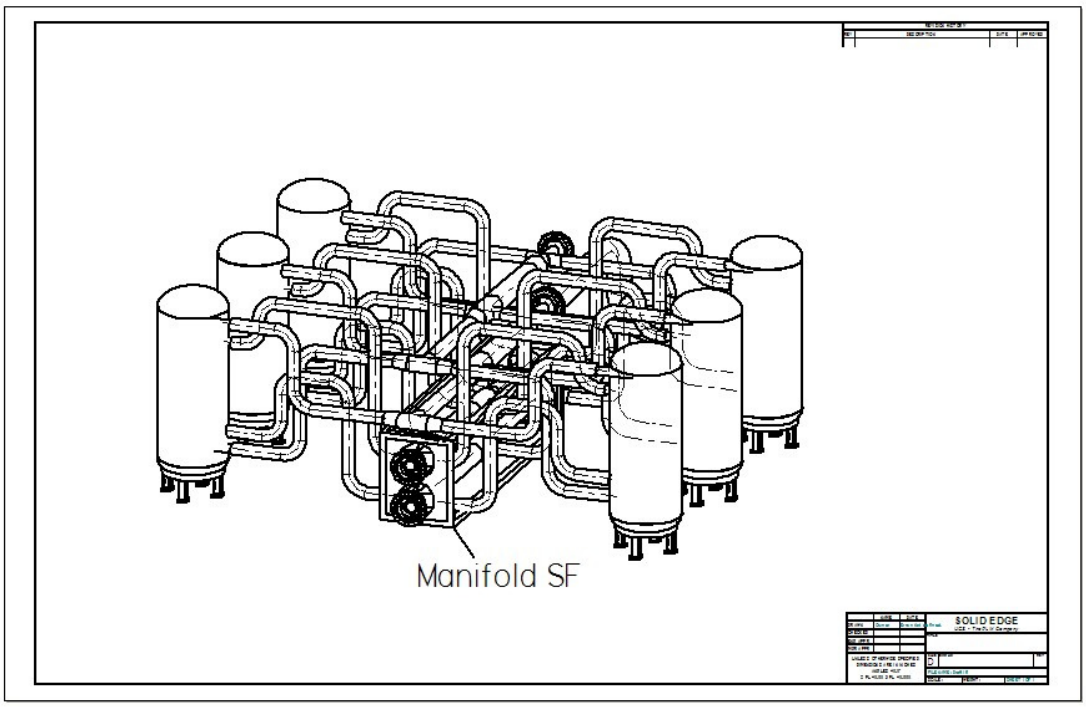

Figure 25: Manifold #1 shown with the Identical Heat Exchangers [Stahle]

4.2.4 Thermal Expansion

During the construction phase of the Pebble Bed Reactor Power Plant, the impact of thermal expansion is benign, as all components will be at atmospheric temperature and pressure. During this part of the power plant's life the above reference system is easy to determine and utilize, however this could become difficult in the face of expanding components due to thermal expansion.

The expansion of piping due to changes in temperature is described in increased length per degree of heat. This growth length has been calculated using CEASAR II in previous work by Berte [Berte]. For the purpose of locations of pipe in our reference system, the connecting pieces are designed with many bends to accommodate theremal expansion. The supports for these connecting pipes are thus actual, fixed, points in the system.

4.3 Procedure for Ensuring Successful Component Interfaces

One of the most important concepts of this thesis is to outline exactly how it can be ensured that parts from one space frame module will connect with parts from an adjacent module in a manner that is both sufficient and economical. There are several steps and concepts involved that need to be followed.

4.3.1 Key Concepts

One key concept is determining tolerances for each component and, in order to compensate for compounding of tolerance allowances, one needs to back calculate that maximum tolerance allowance down to the base component. [GDEB 4] The basic rule of thumb employed at General Dynamics Electric Boat (GDEB) is the 1/3, 2/3/, 3/3 rule. That is, if the final plan requirement for location at completion is +/- 3/8" (3/3), than the in-process tolerance at the sub-assembly level would be +/- 1/8" (1/3) and the tolerance at the module level would be +/- ¼" (2/3). [GDEB 3] For example, if this rule were applied to the PBR, the interface between the component and the space frame would be at most ¼ inch different from the ideal placement of the component. For these space frames, the divergences will be measured relative to the local coordinate system, with the origin located at center of the space frame. The local coordinate system is described in detail in section 4.2.2.

General Dynamics Electric Boat then allows an additional ¼ inch divergence when the module is placed. This divergence is measured using the global reference system described in section 4.2.1. Thus there is a total of ½ inch deviation permitted during plant integration. Tolerances quoted above are only examples of what the real tolerances might be. [GDEB 1]

Another key concept is that of "best fit". Essentially, under the "concept of best fit" a keystone is selected and the modules are placed as close to the exact drawing location taking into consideration any deviation within the module and the overall plant integration requirements. [GDEB 1] The "concept of best fit" is described in-depth in Section 3.1.

4.3.2 Ensuring the Successful Integration of Modules and Their Components

The first step is to ensure that the "concept of best fit" (as described in section 3.1) is incorporated into the planning, design, fabrication and integration phases. It is imperative that there are planned pauses during each step of the process that are used to verify adherence to pre-established tolerances. Analysis is needed using advanced spacial positioning technology and reusable jigs to understand any deviations from specifications in the local grid coordinate system [GDEB 1]. In order to ensure that this critical step occurs, the overall timeline for plant construction needs to include several time periods for these measurements. The following is an overall procedure for the MPBR which incorporates the "best fit" concept while ensuring the successful integration of plant components.

The next step is to fabricate the components and the space frames. In some instances, the components may be manufactured by a different company and then shipped to a central assembly site which will assemble the components to the space frames. In this case, the components themselves will be measured for accuracy, to within ¼ inch. The impact of this step should become less significant as more of the same components are manufactured, as they will be nearly exact replicas of one another. Thus, any imperfections will be constant and the central assembly site can anticipate them (and

drawings/ designs modified if needed). [GDEB 1] The assembly location will place the components in the space frame, ensuring the placement is +/- 1/4 inch of the specification. They will utilize the local reference described in section 4.2.2 when assembling the modules and testing for adherence to tolerances.

The achievement of tolerances can be measured and analyzed in several ways. The component itself can be measured using advanced three dimensional measurement methods described in section 3.5.2. They can also be evaluated by using a reusable, dimensionally verified jig. This jig will be fabricated once and verified for accuracy. The component is then placed on the jig and if within tolerance the jig and component will fit like puzzle pieces. The jig can also be used to transport and place the module on location. Each jig should be re-validated prior to each new use, especially if it is used as a shipping jig. [GDEB 1]

In addition to verifying the location of the component, this planned pause in the process is also an excellent time to test the equipment. The component can be tested in many ways, including hydro-tested, at its fabrication site. This allows for early the detection of any leaks, alignment issues, or unsatisfactory performance. These issues can more easily be corrected at the fabrication site, whereas waiting and determining any problems until the full system is assembled will require either on-site repairs or transportation of the defective component back to the fabrication site. Both of these options are extremely costly. [GDEB 1] General Dynamics Electric Boat has demonstrated that early testing is a major attribute to increasing the ability to stay on schedule and lowers the overall cost. [GDEB 1]

If the component is fabricated at a location other than the module assembly site, testing and measuring will be conducted at the component's origin, and then the component will be rechecked for alignment and operation and tolerances evaluated again after the component(s) are placed and the entire module complete. Again, if there are alignment issues, they should be evaluated at this stage (using the "best fit" approach) to ensure the module will be successfully integrated into the plant.

If the component is fabricated in the same location as the frame and module assembly site the aforementioned measurements and testing can occur at the same location. Again, as before, any corrections that need to be made will occur early and the final module should be easily incorporated in the overall plant when it leaves the assembly plant.

The modules will then be transported using proper shipping and handling tie-down methods to prevent distortion or racking. Once they arrive at the plant site the frames will be placed at the appropriate location, according to the plant floor map, shown in figure 27. This floor map incorporates the local and global reference systems.

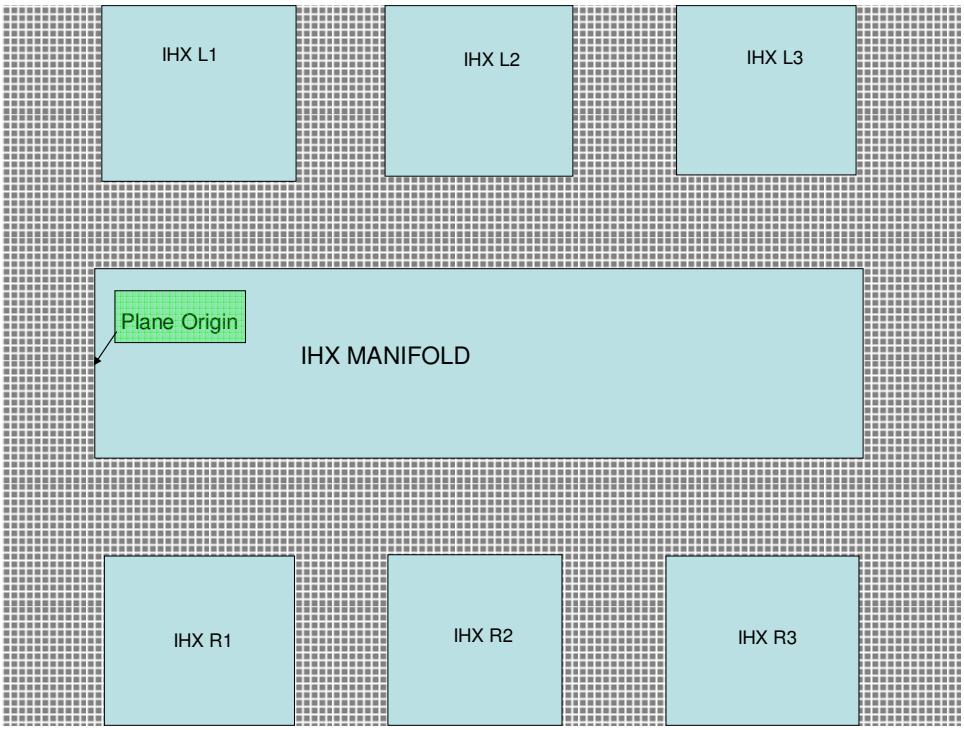

Figure 26: Sample Floor Map

Again, the concept of "best fit" will be utilized. While the floor map shows the ideal placement of the module, if the connecting piping cannot accommodate deviations, the entire assembly can be placed in a slightly different position from its assigned ideal place, based and interfacing locations and using the bulls-eyes for placement. This is

done to minimize any slight imperfections between connecting components. [GDEB 4]. After the module is placed to minimize the differential between connecting parts, the exact divergence will be measured using advanced 3-dimensional techniques that are discussed in detail in section 3.5.

At this point in the process, the modules are placed as close as possible to the assigned grid positions and then they need to be connected. The ability to adjust to any deviations from absolute specifications is the final portion of the "best fit" strategy. During this step there will be two types of connections: direct and indirect.

Direct connections will occur when one frame touches another frame and the components in the frame need to interface with one another. The maximum differential between these to components would be 1/4 inch. This can be overcome by shimming. Direct connections occur only in the power generation side .

All other connections will be indirect. This system of connecting components uses make-up piping which is described in detail in section 5.3. They are based on an assembled space frame locations. The make-up piping, which contains at least five feet of pipe and at least one change in direction, can be fabricated to compensate for the potential ½" difference in all dimensions. The make-up piping is designed into the model such that it can be matched on-site to perfectly fit each of the components and connecting piping. [GDEB 1] The result is an integrated system that can now be fully tested. Again, should any problems arise, only the module that contains the error needs to be worked on.

It is through this procedure- that heavily relies on tolerance adherence and makes extensive use of the "concept of best fit" -that we can be assured that components fabricated around the country will interface successfully upon plant integration.

5 Detailed Space Frame Information

5.1 Intermediate Heat Exchanger Side

MIT's revisiting of Pebble Bed Technology began during a student design project in 1998 [Kadak], during which time the students concluded that it was best to use an intermediate cycle in which the reactor coolant helium was separated from the main power conversion system This allows for great flexibility in the mechanical power conversion system design and is "hydrogen ready" This intermediate stage transfers the heat in the reactor helium to another, secondary, helium loop which is then used for power conversion via electricity creation using high temperature helium turbines.

This section is comprised of 8 separate modules and make up piping. The details of each of these frames in described in this section of the thesis. The global reference plane origin for this section is at the ground level of the Reactor Vessel outlet pipe centerline, where this pipe meets the first space frame, which is offset from the reactor vessel itself by 0.6 meters in the Y direction only. Thus, in global coordinates, the centerline of where the RV outlet pipe meets the RV has the coordinates (0,-.0.60m, 0.765m)

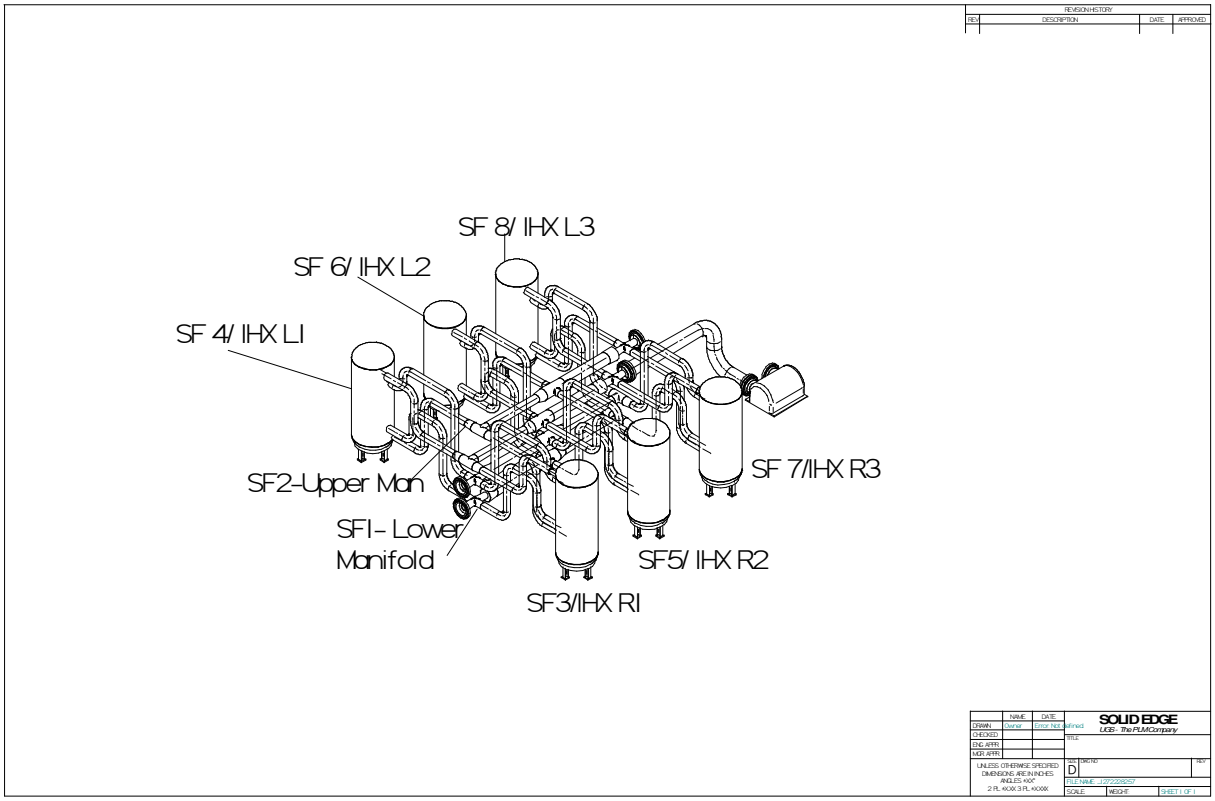

Figure 27: IHX portion of Plant Labeled With Space Frame Numbers and Descriptive Title [Stahle/ Hanlon]

Space frame number one (SF 1) is the keystone for this section and as such it is critical that it be placed exactly as required in the design specifications. To achieve this, additional time and money will be required compared to the placement of other space frames. While requiring additional cost and time, exact placement of the frame so that the frame's primary inlet pipe matches exactly with that of the RV outlet pipe connection in such a manner that the frame can simply lie on the ground (i.e. no adjustments in the Z direction required). This task is accomplished by building in extra time for exact specification adherence on the space frame design and by using advanced precision technology such as photgrammetry and lasers (see section 3.5) .

Space frame number two (SF 2) is the top section of the IHX manifold and will be placed directly on top of SF number one by matching alignment markings on Frame 1 with those on this frame. These marks are located on the space frame itself (See section 4.1 for more information on space frame alignment marks). The maximum deviation of the marks on the two frames should be +/- ½ inch as the bottom module will be placed perfectly in order to act as the keystone for the IHX section of the power plant. The two frames will be connected using bolts that will be drilled directly from the bottom portion of Frame 2 (top module) through the top portion of Frame 1 at points between the supports. The bolts will be pre-drilled in Space Frame 2 in the factory and then joined to Space Frame 1 in the field.

Mechanical supports will be located along the top of Space Frame 2 along the X values of the piping that leads to Intermediate Heat Exchangers. These supports will be attached to the inside of the frame, flush to the original frame and will serve as both mechanical support for the modules, but also as a place to hang structural supports and snubbers for the internal piping.

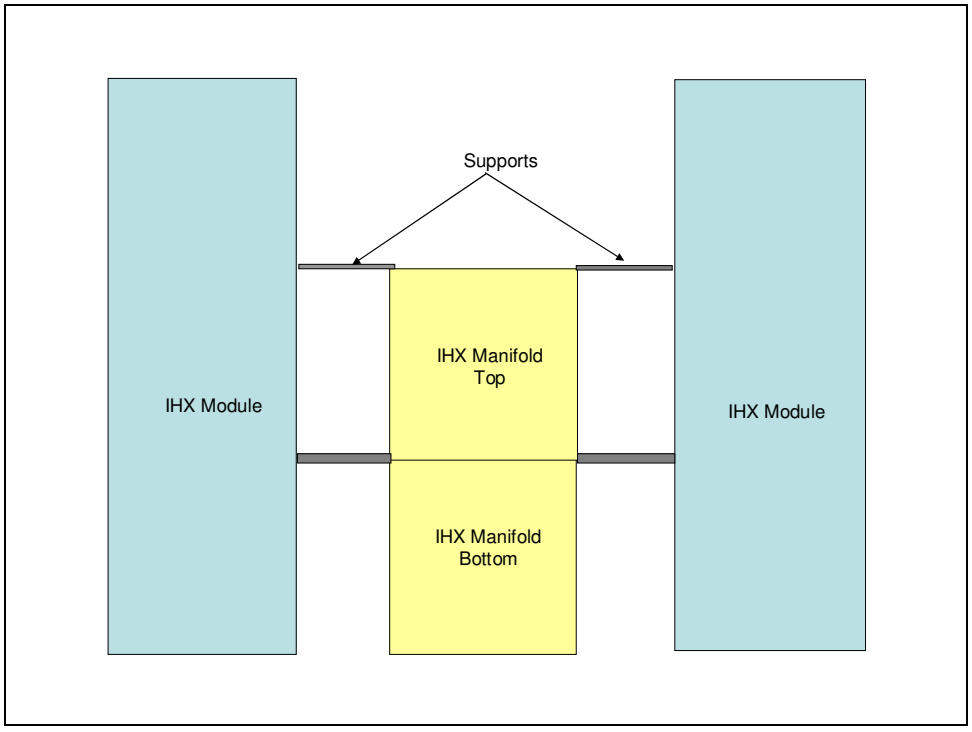

Figure 28: Front View of IHX Modules and Manifold with Support Bars

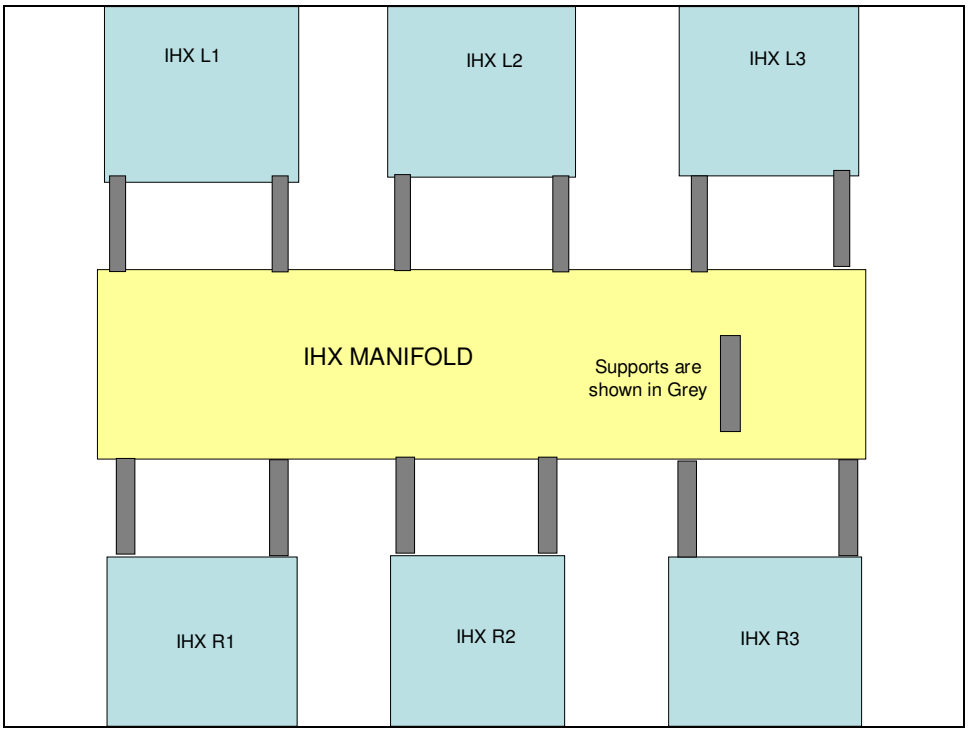

Figure 29: Top Down View of Supports

Between the IHX manifolds and the IHX modules there will also be four supports. These supports will be located on the inside of the IHX space frames on both vertical hollow frames at Z values equal to the top of Frame 2 (i.e. 6 meters from the ground) and the top of the bottom horizontal frame of frame 2 (i.e. 3.2 meters from the ground). These supports will also be used not only for mechanical support of the frames within the system, but also to place the supports and snubbers for the make-up piping between the modules. They are purposely not placed at the X centerline of the frame, since the make-up piping makes several 90 bends, which will be taller than the support locations at times.

5.1.1 Space Frame 1- Lower IHX Manifold

Space Frame 1 is the most critical module on the Primary side of the plant since it contains the reference point for the global system. The centerline for the reactor vessel outlet pipe, which also serves as the frame's local reference system, is the X and Y axis origin. The global Z plane origin is located directly below this pipe's center on the ground.

Figure 31 shows the placement of Space Frame 1 within the entire IHX assembly and Figure 32 shows the module by its self.

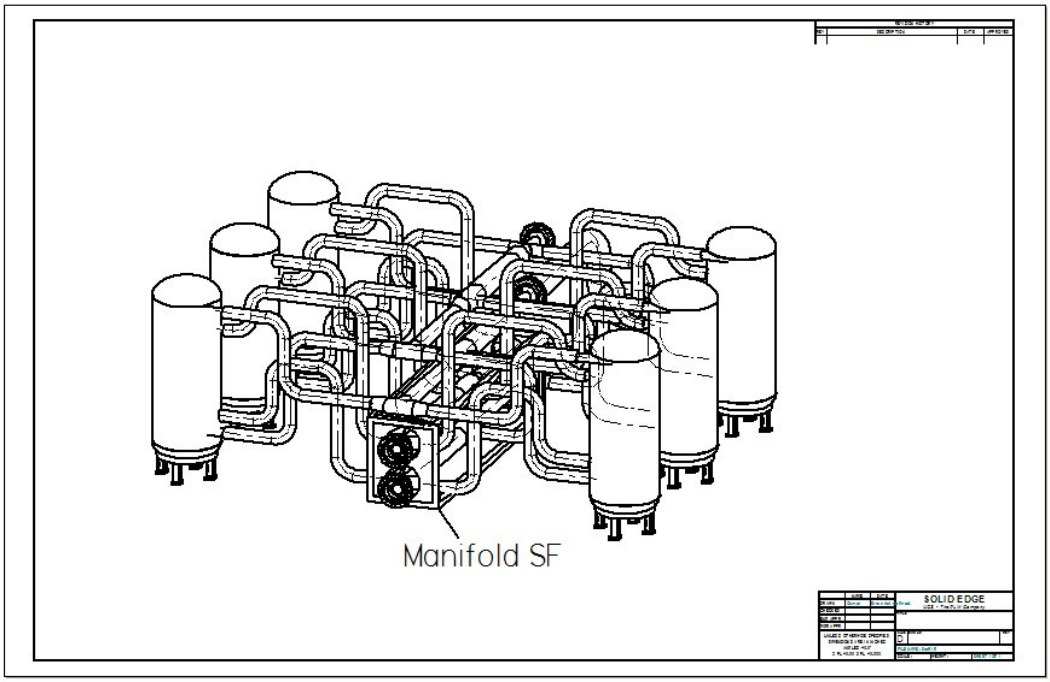

Figure 30: Space Frame #1, Shown Within the Entire Assembly [Stahle/ Hanlon]

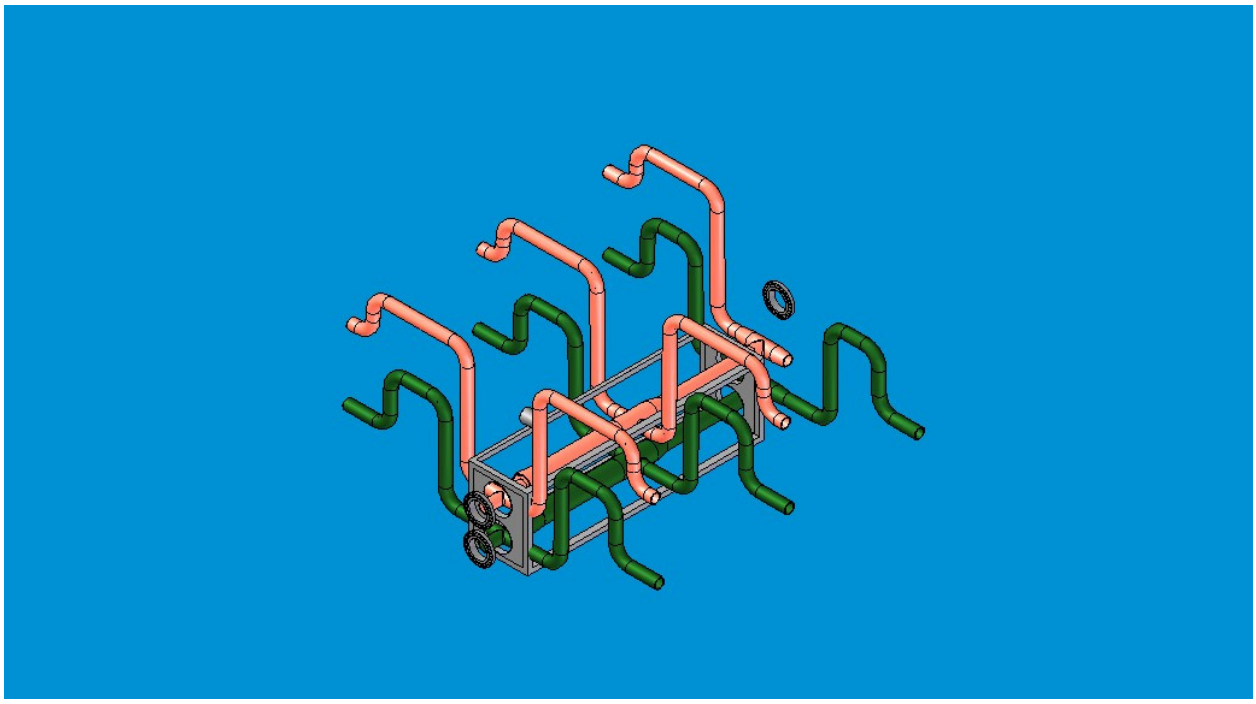

Figure 31: Detailed View of Space Frame 1 and Associated Make-up Piping- Primary Return (Green) and Primary Inlet/ Reactor Vessel Outlet Piping (pink)

Space Frame 1 contains two major pipes, the Reactor Vessel outlet and the Primary return pipes. From each of the main pipes there are three branches-in both the right and left direction- extending to the IHX. From the Reactor Vessel primary inlet pipe there are branches to the IHXs, delivering large quantities of helium. The primary helium is then returned to the RV via the primary return branches that connect to the primary return pipe. Additionally, the inner and outer diameters of these pipes change as they lead to the IHXs, which can be seen in Table 2, located in Section 5.1.3.

Key to the timely construction of the power plant is the precise placement of interfacing components. In the case of the lower IHX manifold space frame, the parts which must mate with components in other modules comprise of the Primary inlet and outlet return pipes leading to each of the six intermediate heat exchangers.

These key components need to be accurately manufactured within the space frame. As stated in section 4.2.2 the coordinate system for each space frame is located in

the dead center of the space frame. The local coordinates for these components are located on Table 1.

Table 1: Table Showing the Local Coordinates of IHX Lower Manifold Interfacing Components for Space Frames 3, 5, and 7.

A	B	C	D (X)	E (Y)	F(Z)
Green pipe (Pri Ret)	10.75 / 16 in ODs	Pipe Center	0	-5	-0.765
Pink Pipe (Pri Out)	10.75 / 16 in ODs	Pipe Center	0	-5	0.635
Gr Pri Ret R1	10.75 / 16 in ODs	Pipe Center	1.25	-5.187	-0.081
Gr Pri Ret L1	10.75 / 16 in ODs	Pipe Center	-1.25	-5.187	-0.081
Gr- PR-R2	10.75 / 16 in ODs	Pipe Center	1.25	0.3	-0.081
GR-PR-L2	10.75 / 16 in ODs	Pipe Center	-1.25	0.3	-0.081
GR-PR-R3	10.75 / 16 in ODs	Pipe Center	1.25	5.786	-0.081
GR-PR-L3	10.75 / 16 in ODs	Pipe Center	-1.25	5.786	-0.081
Pink-PriOut-R1	10.75 / 16 in ODs	Pipe Center	1.25	-5.187	1.328
P-PO-L1	10.75 / 16 in ODs	Pipe Center	-1.25	-5.187	1.328
P-PO-R2	10.75 / 16 in ODs	Pipe Center	1.25	0.3	1.328
P-PO-L2	10.75 / 16 in ODs	Pipe Center	-1.25	0.3	1.328
P-PO-R3	10.75 / 16 in ODs	Pipe Center	1.25	5.786	1.328
P-PO-L3	10.75 / 16 in ODs	Pipe Center	-1.25	5.786	1.328

Coordinates are from the Center of the Space Frame. Column B Describes the Component and Column C Describes the measurement location. Dimensions are in Meters. OD Refers to the Outer Diameter of Two Pipes, with the First Number Corresponding to the Inner Piping's Outer Diameter and the Second Number to the Outside Piping's Outer Diameter. As discussed briefly in section 5.1.2 each pipe is make ups of an inner and outer pipe which are separated by insulation.

Space Frame 1 will be mounted at the exact location of its mapped position using the technique described for Space Frame A in Section 3.2.1. Because removal and replacement of this module will inherently require the shut down of all 6 IHXs and thus the power generation side of the plant, it is considered one module that will not be replaced except under extreme circumstances. Thus, the mechanism for placement, attachment to the ground and the upper manifold module (Space frame 2) will be considered nearly permanent. As with any "nearly permanent" attachment method, the

module can still be removed, but it will take a lot of effort. Because of this assumption that the module will rarely, if ever, be moved permanent mounting will be used. As such, the space frame will be first outfitted with holes for the alignment bolts that are already positioned on the 11X3.5X4 meter plate embedded in the concrete. Additonal bolts will be drilled for seismic and support consideration, as described in Bracing Design A.

5.1.2 Space Frame 2- Upper IHX Manifold

Space Frame 2 will be placed directly on top of Space frame 1, aligned using the frames' respective alignment marks.

In the same fashion as Space Frame 1, Space Frame 2 contains two major pipes, the secondary inlet and outlet pipes. From each of the main pipes three branches-in both the right and left direction- extend to each of the six IHX. As with the primary piping, the inner and outer diameters of these main pipes change as they pass each of the branches leading to the IHXs. That is, after each T in the main pipe leading to or returning from the IHX, the diameter of the main inlet or outlet pipe changes to compensate for the different thermal properties of the helium inside that stems from the heat exchange inside the IHX.

As with other frames, the precise placement of interfacing components from the upper IHX manifold that exit the manifold are critical. In the case of the upper IHX manifold space frame the parts which must mate with components in other modules are the secondary inlet and outlet branch pipes and the secondary inlet and outlet main pipes which carry over to the power conversion system of the plant. These key components need to be accurately manufactured within the space frame. As stated in section 4.2.2 the coordinate system for each space frame is located in the dead center of the space frame. As with all frames, the part location needed to be measured from a designated point in the design and then transferred over to the Space Frame reference system in the center of the module. In the case of Space Frame 2 these measurements were taken from the same point as Space Frame one for consistency.

5.1.3 Space Frames 3-8

Space Frames 3, 4, 5, 6, 7 and 8 refer to Intermediate Heat Exchangers R1, L1, R2, L2, R3 and L3 respectively where R and L refer to the Right and Left sides of the assembly with numbers 1, 2 and 3 relating to the IHX position relative to the Reactor Vessel in the IHX assembly. In keeping with traditional naval nomenclature units on the left (or port) are even, and units to the right (starboard) of the centerline are odd, with numbers increasing with distance from the origin (On a ship the frame most forward, or near the bow, is the lowest, with frame numbers increasing as they move aft).

After each of the first pairs of IHXs, or branches, the diameter of the primary inlet and outlet main pipes decreases from for thermodynamic purposes. The below figure lists the different sizes for the various pipes.

Table 2: Table of Piping Parameters [Berte]

MIT PBR Component	T_{he} (°C)	P_{he} (MPa)	Pipe Temp. (°C)	Pipe Wall Thickness (cm)	Pipe OD (in)
RV-IHX	900	7.73	288	1.156	15.9
IHX manifold after first two branches	900	7.73	288	0.951	13.1
IHX manifold after second two branches	900	7.73	288	0.690	9.5
IHX module primary inlet pipe*	900	7.73	288	0.505	7.0
*IHX vessel***	510	7.59	288	4.584	63.1
IHX module primary exhaust pipe*	510	7.59	288	0.387	5.4
IHX primary cold manifold after 4 branches*	510	7.59	288	0.536	7.5
IHX primary cold manifold after 2 branches*	510	7.59	288	0.746	10.4
IHX to RV primary return*	510	7.59	288	0.913	12.8
IHX secondary hot pipe*	880	7.83	288	1.153	15.6
HPT vessel***	880	7.83	288	2.549	34.4
HPT to LPT	800	6.44	288	0.998	16.3
LPT vessel***	800	6.44	288	2.086	33.9
LPT to PT	720	5.21	288	0.855	17.1
PT vessel***	720	5.21	288	1.680	33.5
Low pressure, hot, recuperator manifold	511	2.75	288	0.540	20.1
Low pressure rec. manifold after 2 branches	511	2.75	288	0.441	16.4
Low pressure rec. manifold after 4 branches	511	2.75	288	0.315	11.7
Low pressure rec. module hot inlet pipe	511	2.75	288	0.226	8.4
High pressure, hot, recuperator manifold	489	7.99	288	0.924	12.3
High pressure rec. manifold after 2 branches	489	7.99	288	0.755	10.1
High pressure rec. manifold after 4 branches	489	7.99	288	0.542	7.2
High pressure rec. module hot inlet pipe	489	7.99	288	0.391	5.2
Low pressure, cold, recuperator manifold	96	2.73	96	0.310	13.7
Low pressure rec. manifold after 2 branches	96	2.73	96	0.253	11.1
Low pressure rec. manifold after 4 branches	96	2.73	96	0.180	7.9
Low pressure rec. module hot inlet pipe	96	2.73	96	0.128	5.7
High pressure, cold, recuperator manifold	70	8	70	0.508	8.1
High pressure rec. manifold after 2 branches	70	8	70	0.415	6.6
High pressure rec. manifold after 4 branches	70	8	70	0.296	4.7
High pressure rec. module hot inlet pipe	70	8	70	0.212	3.4
Recuperator Vessel***	96	2.73	96	1.366	60.3
Precooler to LPC	38	2.71	38	0.267	12.6
Compressor 1***	70	3.57	70	0.929	32.4
Compressor 2***	70	4.67	70	1.215	32.6
Compressor 3***	70	6.11	70	1.590	32.9
Compressor 4***	70	8	70	2.082	33.3

* These pipes lead into the IHX vessels
** These pipes do not require insulation as their operating temperature is below the 288C maximum

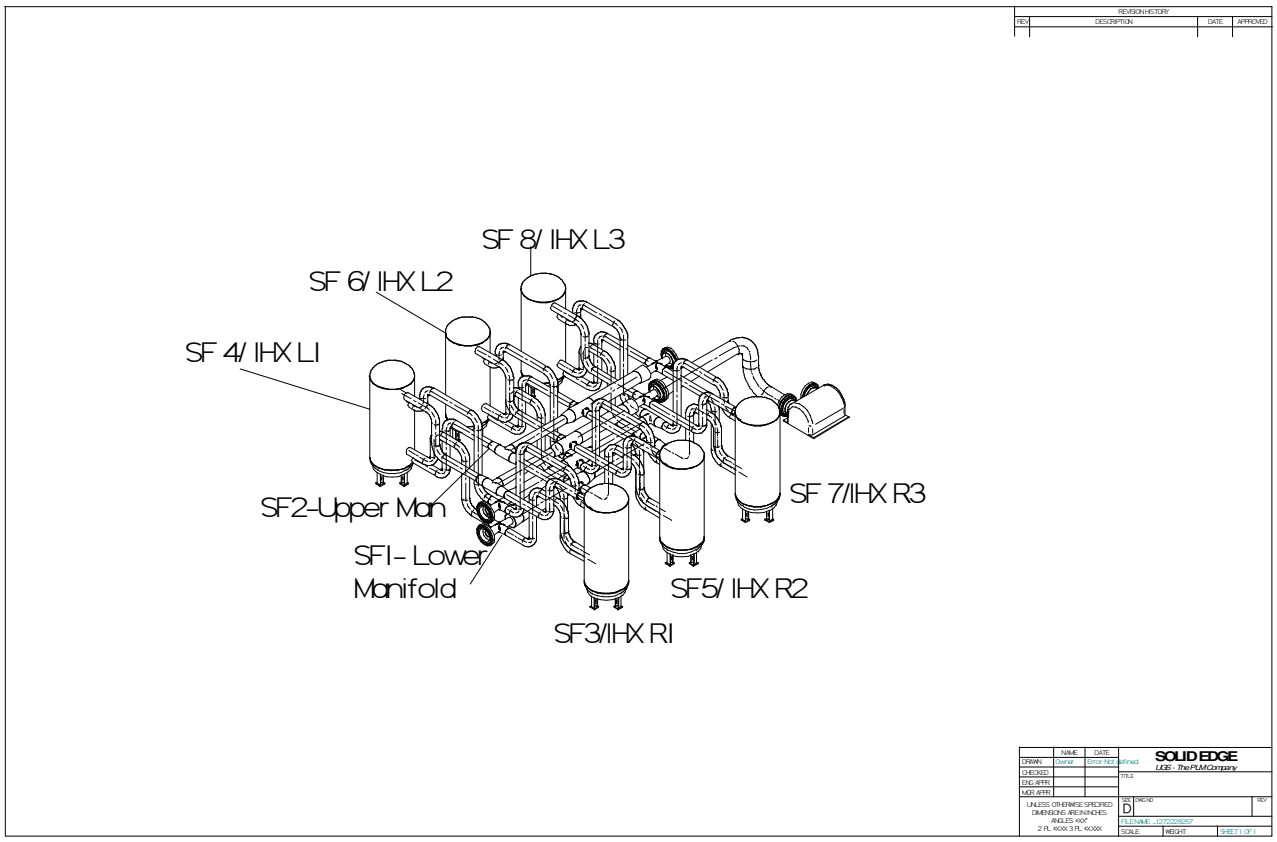

Figure 32: IHX portion of Plant Labeled With Space Frame Numbers and Descriptive Title [Stahle/ Hanlon]

Figure 33 shows the IHX assembly with Space Frames 3-8 labeled with both the space frame numbers and descriptive name.

The Right and Left hand modules of the same number (ie R1 and L1) are mirror images of one another which will greatly aid in our process, as the learning curve for the first IHX can be applied to the subsequent units and units may even be constructed in parallel to one another. The additional savings comes in the ability to utilize the same Space Frame mold and testing criteria for all of the units on one side. As such, Space Frames numbered 3, 5, 7 will all have the same local coordinates. Like wise, Frames L1, L2, and L3 will also have the same local coordinates as the others.

Due to this symmetry, the R1 and L1 modules (frames numbered 3 and 4) will discussed in detail, and the local coordinates of the interfacing components of all frames will be provided.

All IHX space frames have a floor plate on which the IHX is placed. The coordinates for the placement of these legs is also included as part of the critical coordinates calculated, as it is the placement of the IHX in the module which then drives the coordinate for the components that will ultimately mate with the make up piping.

5.1.3A Space Frame 3- IHX Module R1

Module R1 (Space Frame 3) is the basis for all six IHX modules. Figure 31 below shows the module in depth.

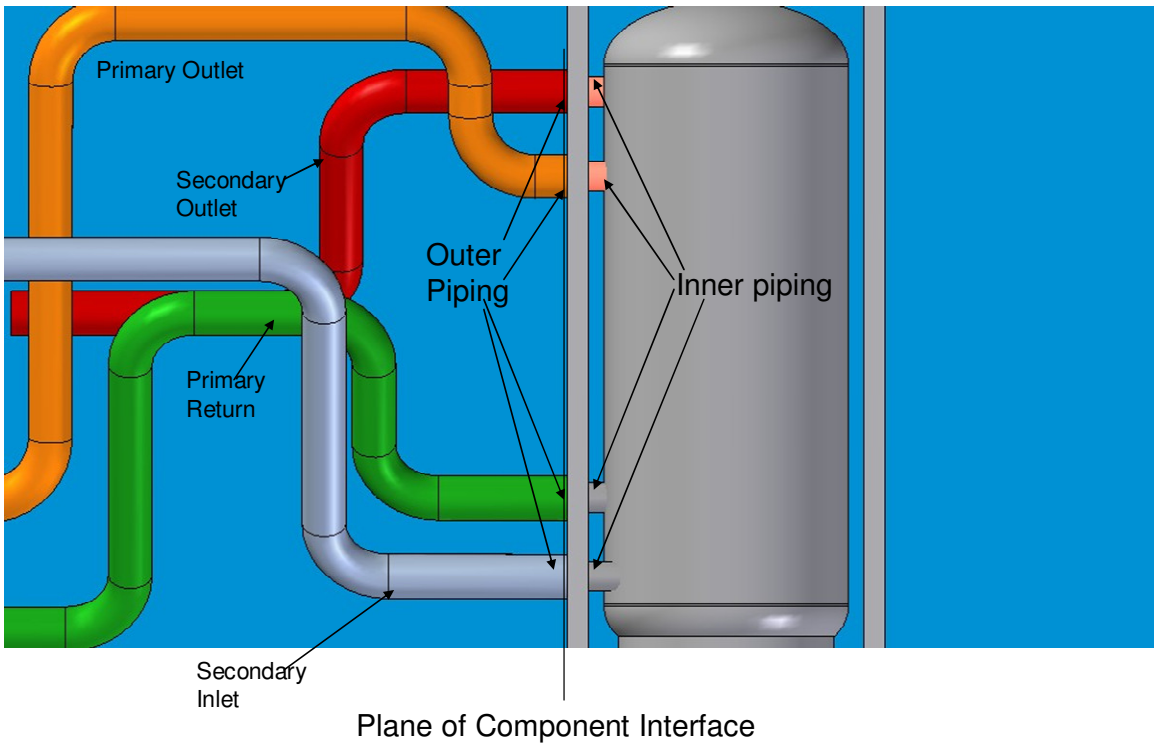

Figure 33: IHX Modules 3-8 and Associated Piping: The Make-up Piping (Shown in Color) Starts At the Outside Plane of the Space Frame.

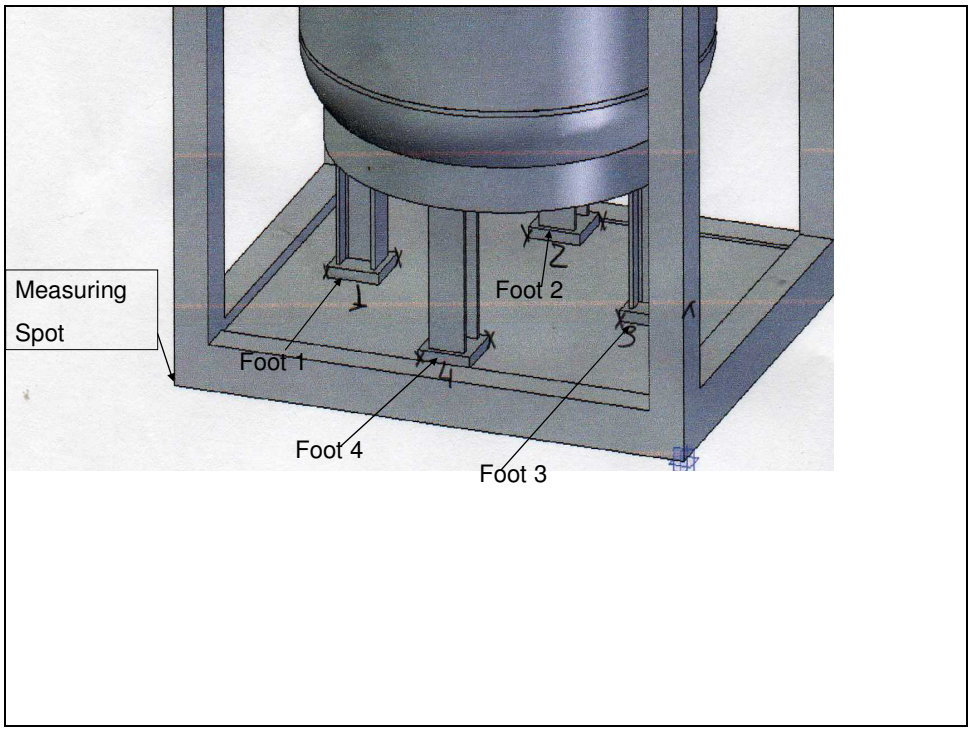

Figure 34: The Base of IHX Space Frame Located on the Right Side of the IHX Manifold, Showing the Spot from Which Measurements were Taken and the Location of the Assigned Feet of the Support

Table 3: Table Showing the Local Coordinates of IHX Supports and Interfacing Components for Space Frames 3, 5, and 7.

			X	Y	Z
Foot1-C	Support for IHX	Corner of foot 1 closest to m O	-1.016	-0.152	-4.7965
Foot 1-F	Support for IHX	Corner of foot 1 Farthest from O-meas	-0.711	0.152	-4.7965
Foot 2-C	Support for IHX	Corner of foot closest to m O	-0.16	0.711	-4.7965
Foot 2-F	Support for IHX	Corner of foot Farthest from O-meas	0.152	1.016	-4.7965
Foot 3-c	Support for IHX	Corner of foot closest to m O	0.711	-0.152	-4.7965
Foot 3-F	Support for IHX	Corner of foot Farthest from O-meas	1.016	0.152	-4.7965
Foot 4-C	Support for IHX	Corner of foot closest to m O	-0.152	-1.016	-4.7965
Foot 4-F	Support for IHX	Corner of foot Farthest from O-meas	0.152	-0.711	-4.7965
Inlet Pipe (grey)	10.75 / 16 in ODs	Pipe Center	-1.5	-0.423	-3.291
Primary Return (green)	10.75 / 16 in ODs	Pipe Center	-1.5	0	-2.5
Primary Outlet (orange)	10.75 / 16 in ODs	Pipe Center	-1.5	0	0.5
Outlet Pipe (red)	10.75 / 16 in ODs	Pipe Center	-1.5	0.5	1.079

Coordinates are from the Center of the Space Frame. Column B Describes the Component and Column C Describes the measurement location. Dimensions are in Meters.

The bottom of the frame is composed of a plate, on which the IHX rests. Besides the placement of the IHX, the other key coordinates include the four pipes that connect from the IHX manifold to the IHX which are, from top to bottom, the secondary outlet pipe (red), Primary outlet pipe (orange/ pink), Primary return pipe (green) and Secondary inlet Pipe (grey). The key coordinates were measured from the space frame corner closest to the RV and the centerline (Shown in Figure 35) and then shifted to the local reference axis, which has its origin at the space point in the center of the space frame.

Table 4: Table Showing the Local Coordinates of IHX Supports and Interfacing Components for Space Frames 3, 5, and 7.

			X	Y	Z
Foot1-C	Support for IHX	Corner of foot 1 closest to m O	-1.016	-0.152	-4.7965
Foot 1-F	Support for IHX	Corner of foot 1 Farthest from O-meas	-0.711	0.152	-4.7965
Foot 2-C	Support for IHX	Corner of foot closest to m O	-0.16	0.711	-4.7965
Foot 2-F	Support for IHX	Corner of foot Farthest from O-meas	0.152	1.016	-4.7965
Foot 3-c	Support for IHX	Corner of foot closest to m O	0.711	-0.152	-4.7965
Foot 3-F	Support for IHX	Corner of foot Farthest from O-meas	1.016	0.152	-4.7965
Foot 4-C	Support for IHX	Corner of foot closest to m O	-0.152	-1.016	-4.7965
Foot 4-F	Support for IHX	Corner of foot Farthest from O-meas	0.152	-0.711	-4.7965
Inlet Pipe (grey)	10.75 / 16 in ODs	Pipe Center	-1.5	-0.423	-3.291
Primary Return (green)	10.75 / 16 in ODs	Pipe Center	-1.5	0	-2.5
Primary Outlet (orange)	10.75 / 16 in ODs	Pipe Center	-1.5	0	0.5
Outlet Pipe (red)	10.75 / 16 in ODs	Pipe Center	-1.5	0.5	1.079
A	B	C	D	E	F

5.1.3 B Space Frame 4- IHX L1

Space frame 4, the first IHX unit on the left side of the centerline is the mirror image of Space Frame 3. Thus, the Y and Z values for the key components for the two units are the same, but the local X values must be opposite in sign from those in space frame 3 to ensure the proper orientation of the frame, as Appendix 1 demonstrates.

IHX L1 is the mold for I HX L2 and L3. Like Space Frame 3, it contains the Secondary outlet, Primary outlet, Primary return, and Secondary inlet pipes, from top to bottom respectively.

5.1.2 Piping

The piping in the IHX and power-conversion sections of the plant utilize pressure backed insulation as required to maintain the piping below 288 degrees C. (Berte) A more detailed discussion of pressured back piping, along with diameter calculations was conducted and is found in Section 5.1 of Marc Berte's 2004 thesis. (Berte). Basically, the design calls for a pipe that is then insulated and surrounded by another pipe, combining the heat transfer properties of the helium, internal pipe, insulation, external pipe and air.

5.3 Make Up Piping

Make Up piping is used between the IHX upper and lower manifold space frames and the Intermediate Heat Exchanger modules. Figure 33 shows the difference in size between the inner helium pipe and the outer pipe, which acts a pressure barrier for the pipes. The piping on inside of the Space frame is the smaller, helium pipe, and the piping outside depicts the outer insulating piping. While both the inner and outer piping will connect to the IHX, in this figure the different pipe sizes are shown for clarity.

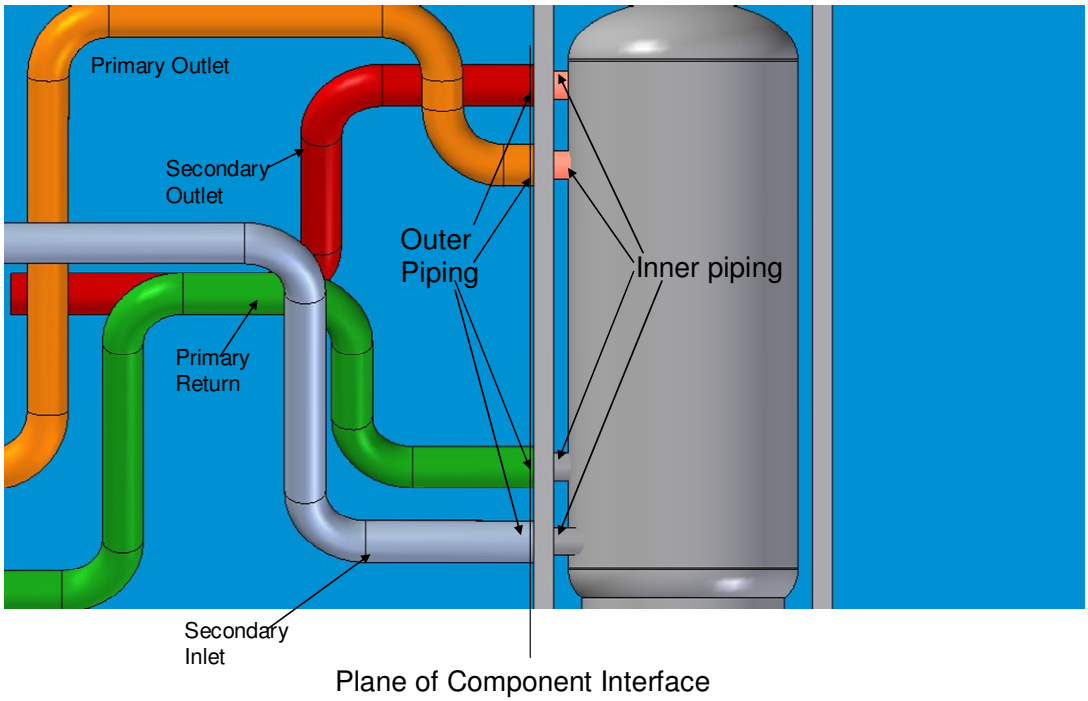

Figure 35: IHX- Close-up

Figure 36 shows the difference between the interior and exterior piping and also depicts how the make-up piping interfaces with piping already in the module. Clearly, the piping shown inside the spaceframe is smaller than the piping shown on the outside of the module.

The pipes that are external to the IHX and manifold space frames are called make-up piping. These pipes are not part of any space frame and installed last, as they serve as a key mechanism to compensate for any alignment issues within the allowed tolerances during the "best fit" process. The pipes are designed to be able to correct for any potential and acceptable deviations from specifications. Each of the pipes shown below will, in practice, be two pipes (when the pipes shown below are cut at the midpoint between the two elbows). Each pipe will enable corrections in one or two directions. As such, as long

as the components are within their design tolerances, the as-designed makeup pipes can correct for the specification variances.

In the event the as-designed pipes cannot correct for the deviances, the exact variance from specs in all degrees of freedom can be determined using advanced 3-D measuring techniques. This information is then programmed into the computer which bends the pipes. As such, the pipes can be "custom" made (based on the ideal design) so the module's components mate up perfectly. The location measurements are taken on site and then sent electronically back to the shop, where they are inputted into the piping software which will update accordingly and create make-up piping that will ensure exact interfaces between components and the piping. Make-up piping can be fabricated in 10 days and is then transported to the site. The entire custom make-up piping process takes 2-3 weeks and, as such, retards the construction process, so it is best if the pipes do not have to be customized.

The pipes between the modules are designed with multiple 90 degree bends in each in order to account for thermal expansion. Make up piping, in order to have the ability to compensate for the up to one inch in all directions (1/2 inch per module) needs to be at least 5 feet in length and contain at least one change in direction [GDEB 3]. As such, the pipes between the modules, which are already designed with bends are perfect for this purpose.

Figures 37-40 below show the designed shapes and rough dimensions or the make up piping in the IHX section.

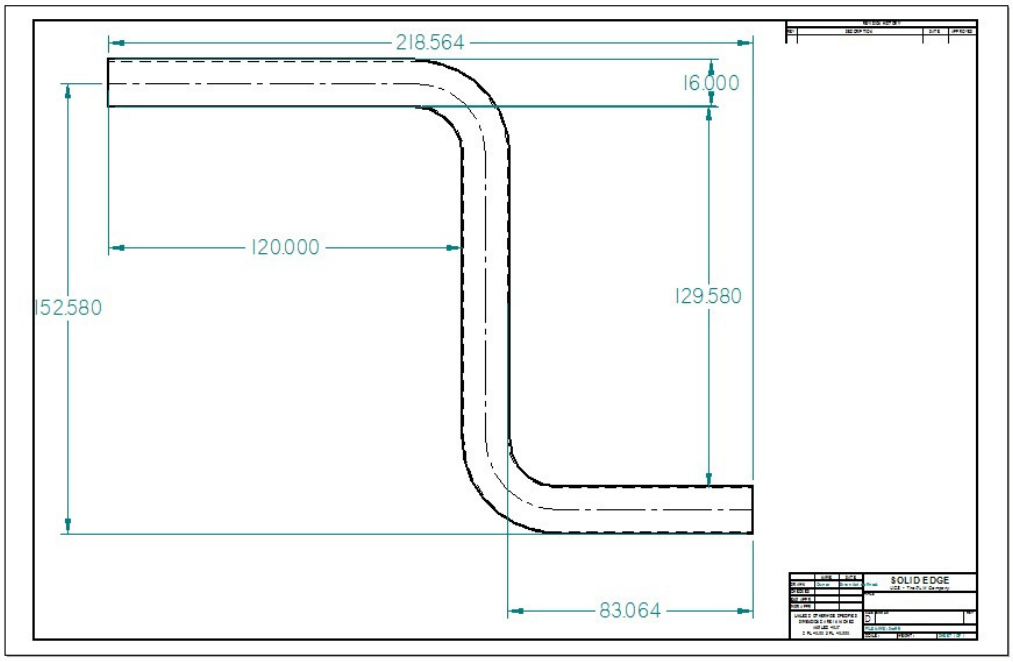

Figure 36: Schematic of Secondary IHX Intake Make-up Pipe (Grey) – Units are in Inches

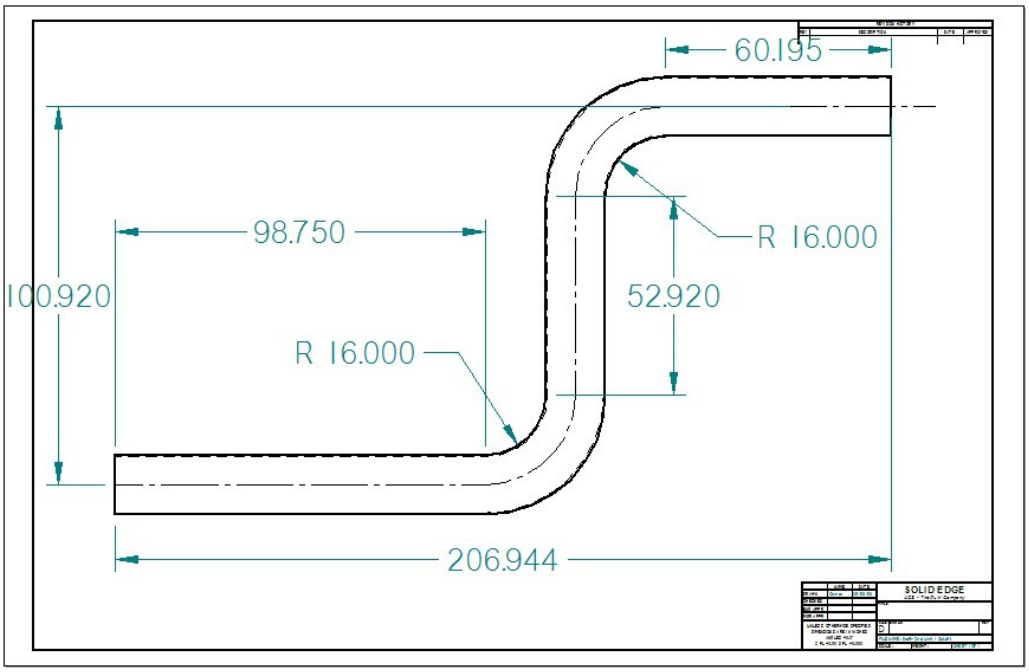

Figure 37: Schematic of IHX Secondary Outlet Make-up piping (red)- Units are in Inches

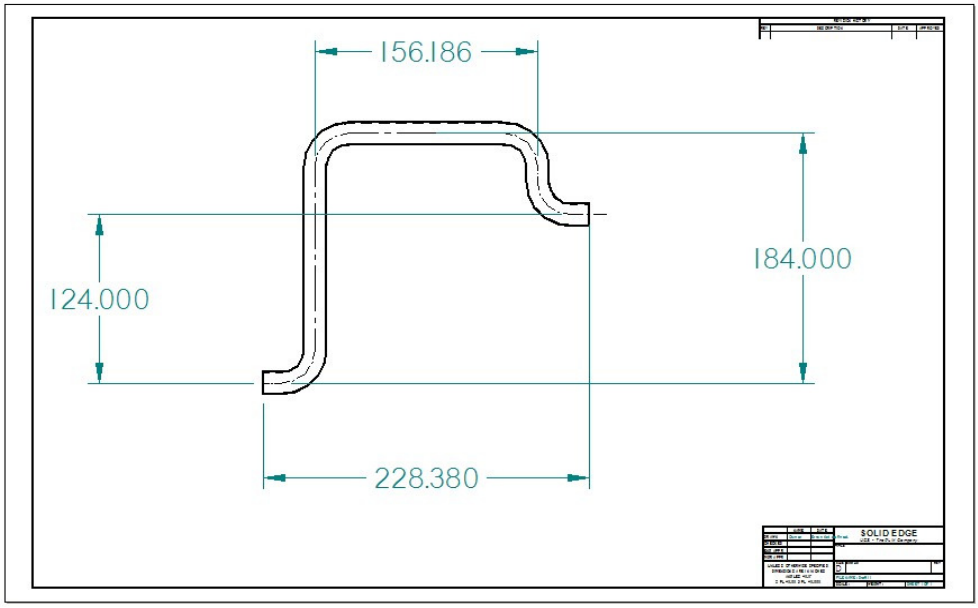

Figure 38: Schematic of IHX Primary Outlet Make-up Piping (orange). Units are in inches

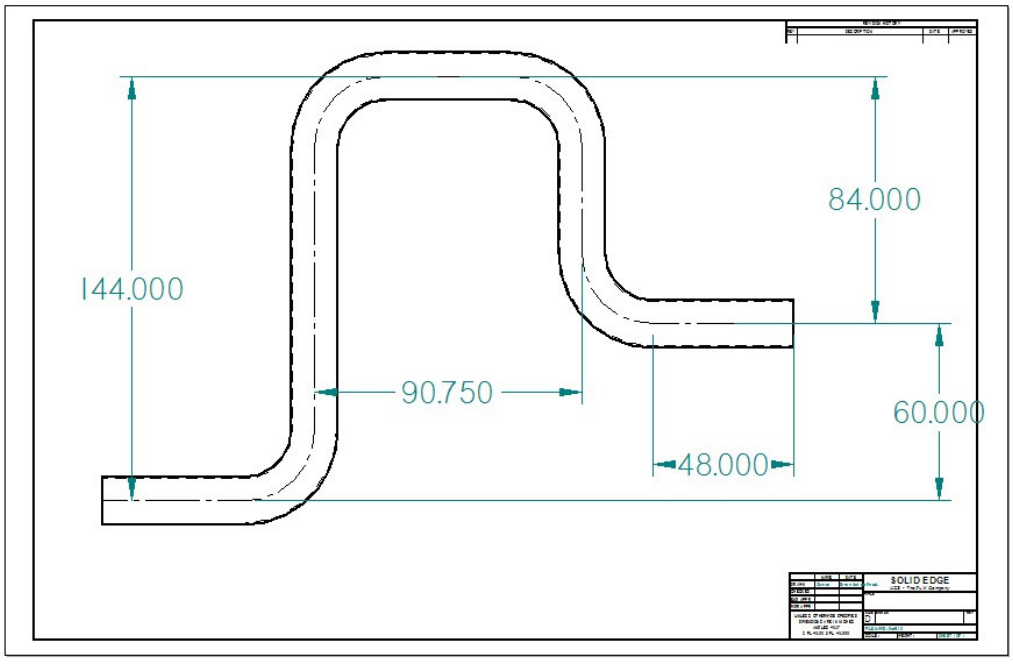

Figure 39: Schematic of IHX Primary Return Make-up Piping (green). Units are in Inches.

It is important to remember that the exact length of the end portions of these make-up pieces can be changed slightly to ensure proper alignment. As such, these schematics serve as the base for the actual pipe fabrication. These makeup pipes will be supported by the additional supports described in section 5.1.

5.2 Power Conversion Side

The power conversion side of the PBR power plant was developed in a more simple matter. Since the purpose of this thesis is to demonstrate that the modules can be fabricated and then successfully mated, the inner working details of the components are not part of the assembly, but rather the rough size of the components with accurate inlet and outlet positions are shown. Also, make-up piping is used as much as possible in order to aid the assembly process.

Figure 41 shows the power-conversion side of the plant. Detailed descriptions of the individual modules follows.

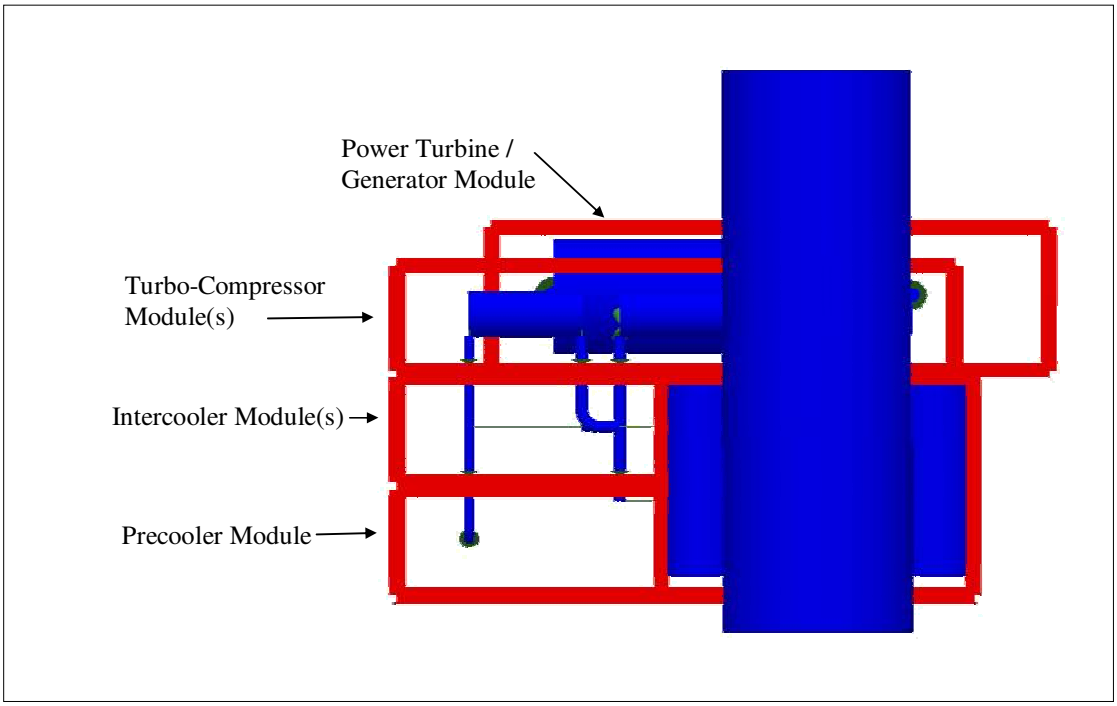

Figure 40: Power-Conversion Portion of Plant [Berte]

5.2.1 Space Frame 9: High Pressure Turbo- Compressor Module

Space frame 9 houses the High Pressure Turbine (HPT) and two compressors. The HPT is connected to the IHX manifold (through a thick wall), the Low Pressure Turbine (LPT) and compressor #1. Compressor #1 is connected to Compressor #2 (both directly and via an intercooler), an intercooler which then connects to Compressor # 4, and the HPT Compressor #2 is connected to Compressor #1 and the recuperator

manifold. Also, both compressors connect to an intercooler housed in space frame 11. [Berte]

The turbine and compressor are very similar in size, having outlet piping at the same height which is at the middle of the unit (.75 m from the base). The length of the compressors is 3m, whereas the length of the turbine is only 2.5 meters. [Berte] The HPT module's space frame is larger than the standard frame used previously. It is 2.5 m X 3.0m x 15.0 m. [Berte] The frame contains a bottom plate with 3.05 and 3.55 m rectangular holes. The plate will support the equipment while the gaps allow for intercooler connections. Figure 42 shows a basic module for the HPT.

The piping that attaches the turbine and compressors to parts housed in other space frames will be installed on site. These pipes will be designed, fabricated and installed in the same manner as the IHX make-up piping.

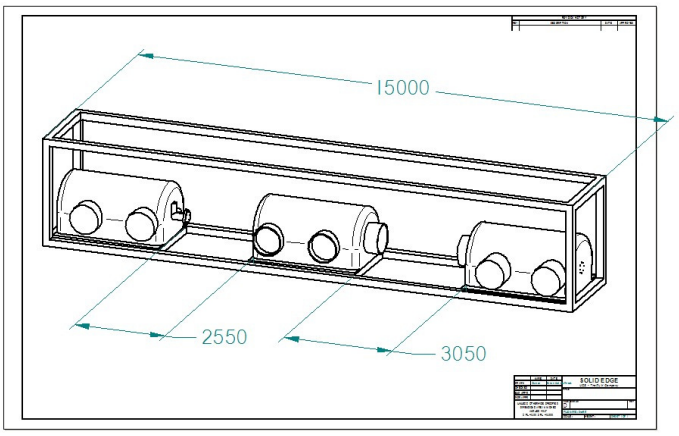

Figure 41: Schematic of Turbo-Compressor Modules (Space Frames 9 and 10) –Units in mm

5.2.2 Space Frame 10: Low Pressure Turbo- Compressor Module

The Low Pressure Turbine (LPT) and its corresponding compressors are housed in Space Frame 10. As in Module 9, the turbine drives two compressors which are separated by an intercooler (which is housed in module 12). The first compressor being

driven (compressor #3) is connected to compressor #4 and the precooler which is housed in Space Frame # 13. Module 10, from a modular standpoint, is exactly the same as module 9. The space frame itself, along with the dimensions and locations of the turbine and compressor interfaces, is the same. This is convenient as the two frames connect. By using the exact same geometry for the interfacing components we can be ensured the parts will interface. [Berte]

5.2.3 Space Frame 11: Double Intercooler Module

Space Frame 11 houses two intercoolers, each of which is 3m wide, 2.5 m high and 1.3 m deep. The intercoolers lay on plates on the base of the space frame. The plate only extends the length of the units to allow for piping. These particular intercoolers are connected between compressor #1 and #4, found in modules number 9 and 10, respectively, and between compressor # 1 and #2 (both in space frame # 9) [Berte] This space frame is the standard 2.5m x 3.0m x 10m size. Figure 43 shows this module. Make-up piping will be used to make these components' connections.

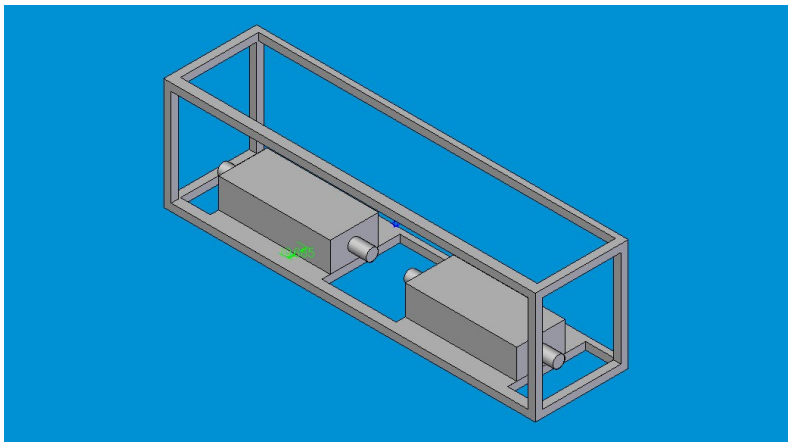

Figure 42: Space Frame 11: the Double Intercooler Module

5.2.4 Space Frame 12: Single Intercooler Module

The single intercooler module, space frame 12, houses one intercooler in a standard-size space frame. [Berte] This intercooler lies on a portion of a bottom plate and

is connected between compressor # 3 and #4. Make-up piping will be used to make this component's connections.

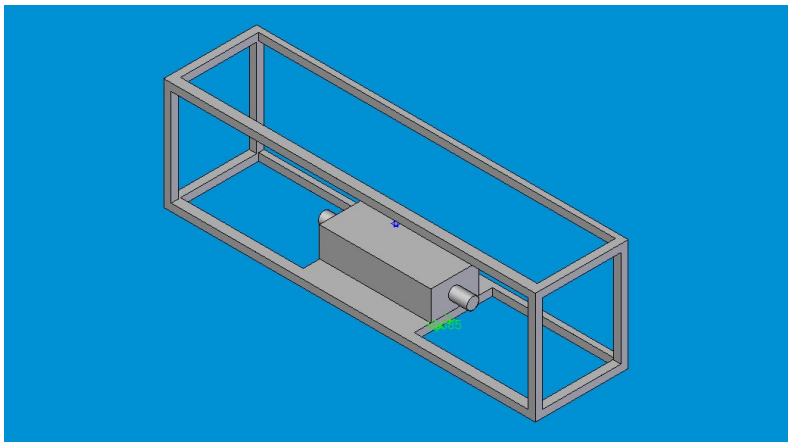

Figure 43: The Pre-cooler/ Single Intercooler Module.

5.2.5 Space Frame 13: Precooler Module

The Precooler module, space frame 13, houses a precooler with the same dimensions as the single intercooler in a standard space frame. Make-up piping will be used to make this component's connections.

5.2.6 Space Frame 14: Power Turbine/ Generator Module

Space Frame number 14 is 10m long, 5m wide and 5 meters tall. It houses the 3.6 m high x4.6 m wide and 4.8 m long power turbine [Berte]. The power spool of the turbine is 3m in diameter and the shaft is located in the center. (i.e. at 0 m Z in the local coordinate system). The power turbine is connected to the generator. In order to support these components a base plate is added. These components are very heavy ($2.03X10^5$ kg for the generator and $3.7X10^4$ kg for the power turbine) but do not require any direct access to components located in lower space frames. As a result, a base plate has been added. This plate will have several medium sized holes in it that will allow for any heat from the recuperators to escape through, while not harming the frames ability to support such a great amount of weight.

The generator is 3.6 m high, 4.6 m wide and 4.8 m long and is housed in the same module. The generator is connected to the power turbine. It is then connected, via make-up piping to the recuperator manifold. This make-up piping includes two bends and exceeds the 5ft requirement for make-up piping. This piping will be very heavy and as such will need to be supported. To facilitate this, a space frame pipe will be fabricated as part of the upper recuperator manifold module and used to install supports for this pipe. Also, since much of this pipe will be not located directly above or next to any module, (see figure 46) supports will need to be hung from the wall of the power plant structure itself. Berte had proposed outfitting two space frames with pieces of the generator. One module would house a completely straight pipe and the other would house the bend. While these modules would provide support for the generator pipe, ensuring the pipe pieces would fit together directly (especially the one module with the straight pipe) would be extraordinarily difficult and expensive. As such, it is best to treat the generator pipe as make-up piping and have it supported by supports connected to the plant structure (which can be added at any point during the construction process).

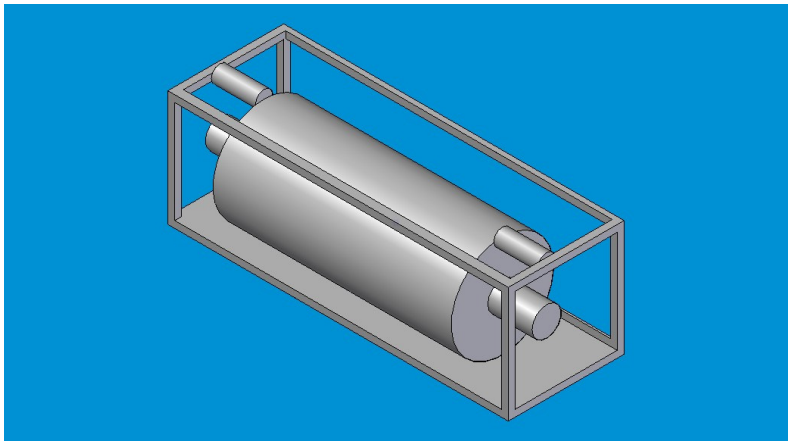

Figure 44: Space Frame 14: Power-Turbine Module

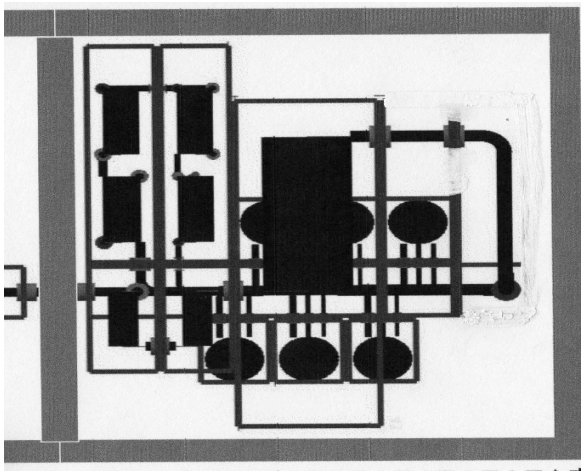

Figure 45: The Entire Power Plant, Highlighting the Placement of the Generator Pipe. [Berte and Hyssong]

5.2.7 Space Frame 15: Recuperator Manifolds

The recuperator manifolds greatly resemble those used in the IHX side for the Intermediate Heat Exchangers. As such, the same approach is used. Since the recuperators are nearly identical to the IHX components the assumption of the manifold modeled in section 5.1 is appropriate. [Berte].

5.2.8 Space Frames 16-21: Recuperator Modules

The recuperators will fit into modules that are the standard 2.5m by 3.0m wide and deep, but only 6 m tall. This allows for their height to be the same as the stacked manifold modules and the stacked intercooler and precoolers modules. Thus the turbine modules will lay on top of the recuperator modules and the stacked manifolds and intercooler and precooler modules. [Berte]

The recuperator has a hexagonal arrangement of core modules that are encapsulated in a 2.3 m diameter vessel that has a gap which allow for the internal piping to mate with the manifold pipings [Berte]. Even though they are taller, the recuperators'

distribution is identical to the IHX distribution and thus we can use the IHX manifold approach previously described in section 5.1.

5.3-Space Frame 22: Heat Rejection Module

The heat rejection module is 3m tall and 10 long. On top of the module is a 1 m tall louvered chimney that is installed on site and below the module is a system of 10 forced draft intake fans. This module stands separate from the power conversion assembly and thus does not need to be modeled as part of this thesis.

6 Cost Analysis

This section analyzes the possible cost reductions for building a Pebble Bed Reactor in a modular fashion instead of using a traditional or "stick build" process. General construction cost principles are discussed, followed by a comparison of techniques used, results achieved by the submarine construction industry and the potential impact upon the construction of PBR power plants.

6.1 Principles of Construction Economics

The main controllable economic factors in construction are time and labor. Not only the sheer number of manhours required to complete a job, but also whether the tradesmen will be paid a premium wage. Also, the environment in which personnel will be working will affect their productivity.

It is generally accepted that for normal construction project that as the schedule lengthens the cost increases. This is because more employees will be assigned to the job for longer periods of time. There are times, however, where decreasing the schedule length will in fact increase the cost. When overtime is utilized inefficiently the project cost will soar, even though the schedule should theoretically shrink. For this analysis, it is assumed that overtime is used only as required to make-up for schedule and delays and thus focuses on the overall manhours expended on a project.

6.1.1 Economic Benefit of Modular Vs. Traditional Construction Methods

This section looks at the processes used and economic benefits seen by General Dynamics Electric Boat when the corporation switched from building submarines in a traditional fashion to their current modular construction process. Then, the construction of submarines and that of a PBR power plant are compared and finally some anticipated cost savings for building the PBR in a modular fashion is discussed.

Please note that all values in this section are Engineering Rough-Order-of-Magnitudes (EROM) and meant to be estimates, they have NOT been rigorously developed and are NOT meant for guaranteed savings, but rather a broad measure for possible savings based on past construction work. [GDEB 1]

6.2 Submarine Construction Example (General Dynamics Electric Boat)

This portion of the cost analysis section examines the traditional method used by the submarine construction corporation used in the past. It then looks at the company's current methods and cost-saving strategies. Finally, the economic results of these changes are discussed.

6.2.1 Traditional approach

Traditional submarine construction consisted of bringing nearly all material to the construction site (construction yard) and setting up the construction site. First, the hull was constructed. Hull cuts were then made to support the installation and integration of the various systems and equipment. This traditional technique of top loading the submarine required expensive hull cuts and was highly inefficient. There constantly were work delays since there was limited amount of space to access the submarine and once inside, and extremely limited amount of work space for installation. If not sequenced perfectly, and even with proper sequencing, one component may need to be removed in order to support the installation of equipment in the surrounding area. Further, hot work and other dangerous construction activities severely limit the workable area of the submarine while it occurs. These all lead to lengthening the schedule, which increases the overall cost. Further, premium cost, highly skilled tradesmen, such as pipe welders are forced to work in a less than perfect environment, which leads to rework. Further, they may be delayed from starting or completing work due to workspace conflicts. [GDEB 1]

6.2.2 General Dynamics Electric Boat Goes Modular

Faced with a shrinking budget and a new, constantly changing requirements, General Dynamics was forced to change they way they conducted business. They moved away from the traditional construction methods and started to build the submarines in modular fashion. [Carey]

They designed the submarine's key internal systems into self-contained units that are built and tested off-site in a shop environment. This allows premium, skilled tradesmen to operate in a highly conducive work environment that not only eliminates schedule conflicts with surrounding work, but also provides the tradesman with ample space to perform skilled work. [GDEB 2]

General Dynamics makes extensive use of reusable pipe fixtures in the fabrication shop. These fixtures offer a key control mechanism during the fabrication process, as they allow the shop personnel to see if their product fits properly (i.e.deviations can be measured and connections to joining parts tested). Further, as the fixtures are reusable they provide needed consistency throughout the fabrication process. [GDEB 1]

Electronic bend data with predetermined fitting to fitting are identified. This allows the fabricator to take advantage of Computer Numerically Controlled (CNC) bending machines and eliminates the need for manual calculation, which takes time, and leads to errors. This is used for piping that is contained in the space frame, but is also used for the fabrication of the make-up piping. As tolerance data is measured in the field and recorded electronically, any variations from the original pipe design can be incorporated and the CNC bending machine used to bend the new pipe. These pipes can be fabricated in the shop with great ease and then transported to the site where they are installed. [GDEB 1]

With an extensive design, components can be fabricated in the shop and assembles with other components at a different site. The advanced three-dimensional measuring tools described in section 3.5 are used along the way to ensure that the components, and then the assemblies/ modules meet the predetermined tolerances.

Using the same concept, components and modules can be fabricated and assembled at various locations and then integrated at the final construction site. This is the procedure used for the current line of submarines being constructed. Currently, both General Dynamics and Newport News ship building fabricate and assemble designated modules. Each corporation fabricates and assembles the same sections each time for each new boat. The sections are then shipped to the construction site (which alternates between the two yards) and integrated into the final product. In order for this to occur with minimal delays and rework, both companies need to be provided detailed drawings of mating components and adhere to the same tolerances. [GDEB 2]

6.2.3 Economic Benefits

General Dynamics Electric Boat (GDEB) has realized a net cost savings of approximately 30% [GDEB 1] using modular versus traditional construction. This savings is realized for many reasons.

One concept that attributes to this savings is the law of mass production. By being able to make identical components, lessons learned can be incorporated and a learning curve established. Also, once a component is fabricated within tolerance (i.e. the process is acceptable) it can be fabricated time and time again with little concern for departure from requirements.

The sections are able to be built in parallel to one another, which shortens the overall length of construction. Also, by having as much premium labor accomplished in the more conducive shop environment, the amount of skilled labor at the construction site where delays can be expected and the work environment is degraded is minimized and thus premium labor costs reduced.

The accessibility of the sections in the shop and assembly environments is much greater than in a traditional construction unit. This leads to easier construction, and requires less awkward positioning to accomplish difficult tasks. Thus, the quality will be higher, costly rework less, and completed quicker. [GDEB 1]

6.2.3 Rule of Thumb for Work

General Dynamics has demonstrated a rule-of-thumb for work expense at different locations. The so-called "1-3-8" rule is described below and encapsulates how modularizing construction leads to a reduced delivered cost.

Essentially, a job which takes 1 hour to accomplish in the shop, takes 3 hours to complete in module, and an extraordinary 8 hours to accomplish on site! The 8 to 3 hour ratio is dramatic enough, but if as more work is accomplished in the shop, an even greater 8 to 1 hour savings can be seen! Figure 47 below visualizes this metric.

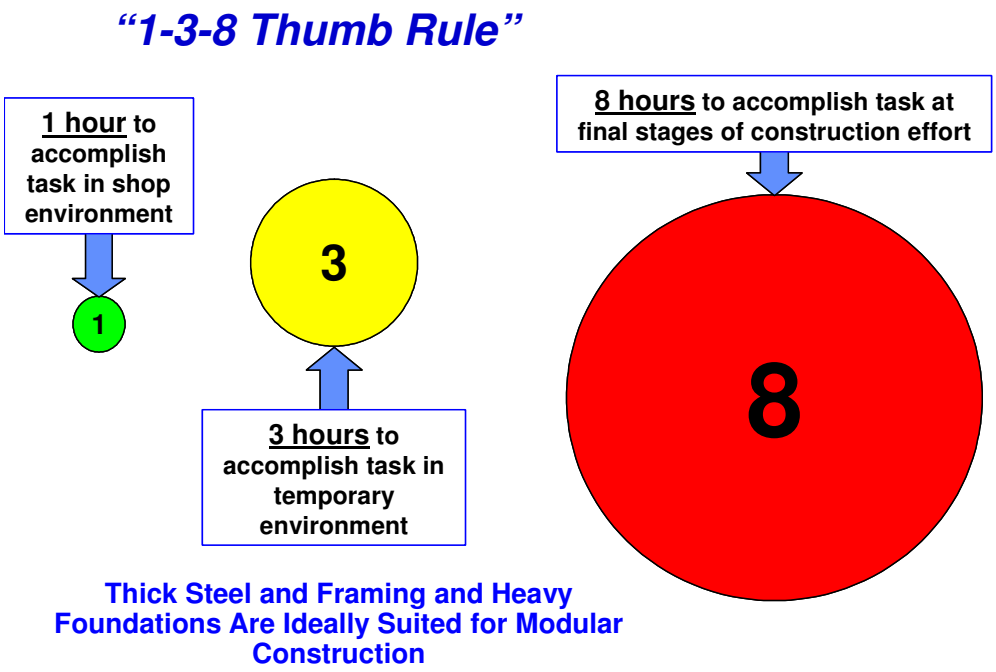
"1-3-8 Thumb Rule"
1 hour to accomplish task in shop environment
1
3
3 hours to accomplish task in temporary environment
8 hours to accomplish task at final stages of construction effort
8
Thick Steel and Framing and Heavy Foundations Are Ideally Suited for Modular Construction

Figure 46: General Dyanmics' 1-3-8 Rule

6.2.4 Summary of Economic Findings For General Dynamics

A dramatic net cost reduction of 30% has been realized by General Dynamics Electric Boat. As seen in figure 48 the number of manhours decreased by more than 50%, (from 23.3- 10.0 million) from the construction of the SEAWOLF to NEW

HAMPSHIRE. Figure 49 demonstrates the 30% decrease labor cost seen by GDEB upon transition to modular construction.

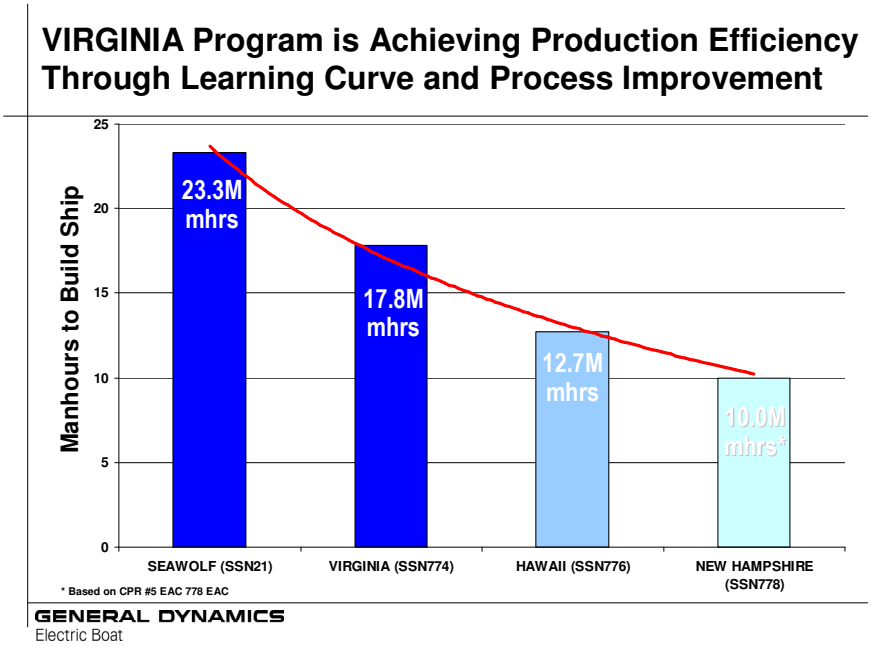

Figure 47: The Decrease in Manhours Used to Deliver a Submarine[GDEB1]

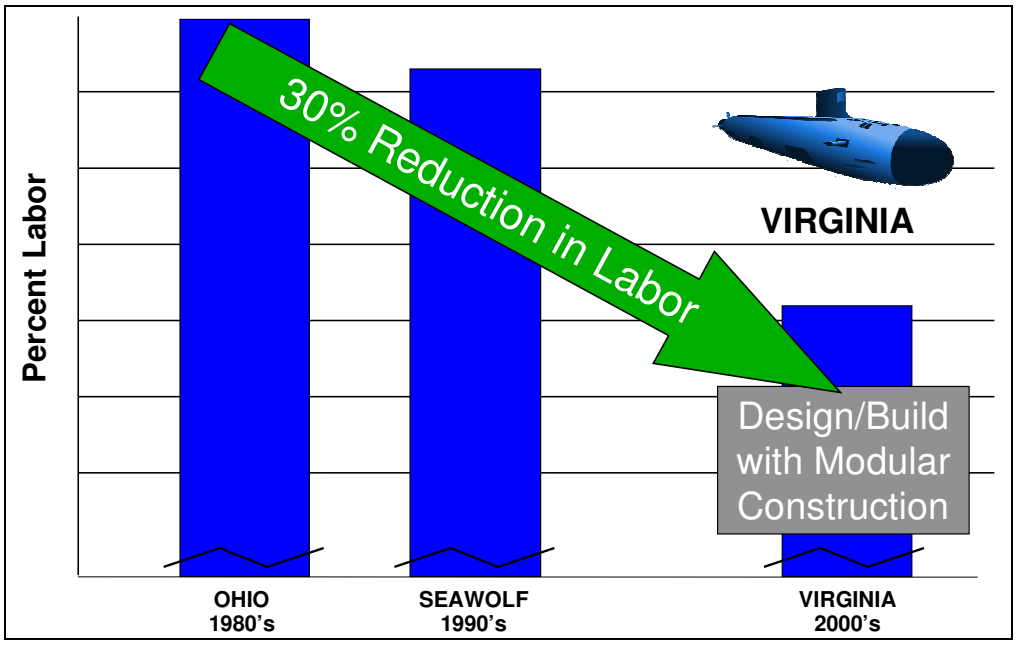

Figure 48: Percent Labor Cost for Traditional and Modularly Constructed Submarines [GDEB 1]

6.3 Economic Effect of Modular Construction of the Pebble Bed Reactor

This section will discuss the past "stick build" traditional methods of power plant construction and how to transition to a modular approach. It was be demonstrated how modularizing the PBR relates to the transition made by General Dynamics' construction techniques. Finally we will estimate the extent to which the cost savings realized in the submarine construction business may be expected by building a PBR in a modular fashion.

6.3.1 Traditional Power Plant Construction

Traditionally, nuclear power plants are built in a "stick-build" fashion, in which most of the labor occurs at the construction site. Individual parts are fabricated and then measured and made to fit on site. All components were made separately and, when incorporated, are intimately part of the entire plant, making it difficult to isolate or

replace. Often they are built from the outside- in by building the superstructure first and then "filling it" with the "guts" of the plant. Since traditional nuclear power plants were unique from one another, their construction methods did not take advantage of mass production, standardized parts, or necessarily incorporated lessons learned.

6.3.2. Modularizing the Pebble Bed Reactor Power Plant

This thesis has been an in-depth look at modularizing the PBR. It has shown that components can be fabricated and then assembled into space frames, forming modules, either at the location of component fabrication or at a project integrator. These modules will then be transported to the construction site and assembled to form the power plant. Make up piping will be used between the space frames that do not directly contact each other and act a compensation mechanism for any derivations from specifications that are within the design tolerances. Components and modules are to be tested for operation and shape multiple times during the process. Several advanced 3D measuring techniques will aid this process.

6.3.3 How PBR and Submarine Construction Compare

This thesis has focused on employing the processes successfully developed and applied by GDEB in incorporating modularity in constructing submarines. But, how does constructing a Nuclear Pebble Bed Reactor Plant compare to a submarine?

A US Nuclear power submarine is an extremely complex machine. It houses many complicated electronic, combatant, and mechanical systems. Instead of being housed in a facility with walls, its outer environment is sealed through two hulls which keep its crew safe during daily and combatant activities. Thus, construction of a nuclear submarine is more complex than that of a land-based power plant. The key, though, is that the aspects which GDEB modularized in the overall concept of construction are very similar. In both cases, instead of building the unit from the outside-in at a construction site, the system is broken in individual units, which contain components that can be fabricated at various locations and then assembled. These units, or modules, are then transported to the construction and site and integrated with the other modules to comprise

the finished unit. In both cases, components and units are tested for tolerance adherence and operation at the earliest point, and a system for addressing any deviation from specifications is in place to ensure the modules successfully integrate.

Both systems take advantage of in-shop productivity while minimizing on-site labor, especially among costly, skilled trades. Both also optimize the work environment which enhances safety and quality work. Additionally, the ability to exchange units or upgrade is inherent in both submarine and PBR power plant construction concepts. Finally, General Dynamics Electric Boat's current operation with another construction yard parallels the concept of having different companies manufacturing different components and modules.

Thus, the transformation from traditional to modular construction used by General Dynamics Electric Boat can easily be translated to the Pebble Bed Reactor. As such, the last part of this section relates how much of the submarine construction savings can be anticipated for the PBR based on the extent of parallels.

6.4 Potential Modularized PBR Cost Savings

Can the dramatic 30% cost savings realized by General Dynamics be expected by modularizing the PBR? Given that many of the concepts and design factors of the submarine construction parallel those proposed by the PBR similar savings may be anticipated. But just how much?

The fact that nature of submarine construction is more complex than construction of a nuclear plant, (due to the more complicated systems, limited space, and changing requirements of the submarine's mission and therefore equipment), the opportunities to reduce construction cost areas (reducing the number of joints/ welds by reconfiguration, etc) are not as readily available in the simpler MPBR power plant. Thus, while the full 30% magnitude may not be realized initially, a significant savings can still be expected. Additionally, it is expected that by taking advantage of the shop environment, these processes will promote safer, high quality fabrication. [GDEB 1]

Obviously the first plant to be built will require more planning and design than future plants. Further, the initial plant will inherently experience more complications during its construction. These initial impediments should be minimized in future plants by incorporating the lessons learned. When the surface ship construction company, NASSCO (General Dynamics National Steel and Shipbuilding Company) incorporated the concepts shared by Electric Boat, they realized an initial 25% savings, with increased saving anticipated. [GDEB 1]

As such, even though an exact savings cannot be calculated because of the variables at hand, a significant savings of at least 20% can be expected with this saving increasing as more plants are built in this manner.

7 Summary of Work and Areas for Future Work

7.1 Summary

This thesis examined current engineering techniques and concepts being applied to modular construction and then applied them to the MIT Pebble Bed Reactor in an effort to demonstrate the modular concept can be applied to such a project. Further, the individual space frames were designed, with detailed component locations and interfaces. Finally, a cost analysis was performed which used information from submarine construction and analyzed the parallels between the two projects. The results show that the modularity techniques proposed through the use of space frames can work with the needed accuracy which may yield cost savings of at least 20%.

7.2 Areas for Future Work

While this thesis demonstrated the theoretical construction of the PBR as a modularized power plant, there are still many areas for further research and work that should be explored.

One of these areas is to consider the seismic requirements of nuclear power plants. While this thesis proposed support systems and their placement, these proposals were not seismically analyzed.

Another area for further work is to design the module replacement procedure. This will need to include not only the support systems needed to remove a module, but also the steps for the re-installation of another unit. More complicated is the design of the by-pass systems that will need to be in place in order to isolate components (for maintenance or replacement). This bypass system will need to include not only the additional piping, but also an in-depth analysis of valves and there ability to seal high temperature helium.

The valve development for this system could be a project in itself, as current materials are being developed and improved to withstand the high temperatures proposed in this design without the potential for failure (and therefore radiation leakage).

The exact and very detailed design and construction timeline should be drafted. This timeline should factor in all of the benefits of modularity but also to consider the time needed to make the needed measurements to assure lineup as part of the accuracy control program.

Lastly, the modularization of the other large component, namely the reactor vessel should be made which should include the refueling system to take full advantage of this approach.

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